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SECTION 27

LIGHTNING AND OVERVOLTAGE PROTECTION

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27.1 INTRODUCTION

Temporary overvoltages in power systems occur for a variety of reasons such as faults, switching, and lightning. By far, the most severe overvoltages result from lightning strokes to the power system. Most likely, lightning overvoltages will be very high, resulting in insulation breakdown of power apparatus with destructive results. It is therefore imperative that power systems be designed in such a way that expected overvoltages be below the withstand capability of power apparatus insulation. Many times, this basic requirement is translated into excessive cost. For this reason, one seeks a compromise in which power systems are designed in such a way that the possibility of destructive failure of power apparatus due to overvoltages is minimized. This procedure is based on coordinating the expected overvoltages and the withstand capability of power apparatus. Two steps are typically involved: (1) proper design of the power system to control and minimize the possible overvoltages and (2) application of overvoltage protective devices. Collectively, the two steps are called *overvoltage protection* or *insulation coordination*.

The importance of overvoltage protection cannot be emphasized enough. First it affects system reliability, which translates into economics. Traditionally, overvoltage protection methods were guided by the objective to maximize system reliability with reasonable investment cost. In this sense, transient overvoltages which do not lead to interruptions are acceptable and short-duration interruptions are tolerable. Recently, however, with the introduction of sensitive electronic equipment, new concerns have been raised. The issue of power quality is important and it is transforming the practices for overvoltage protection. While the application of overvoltage protection devices is pertinent, more and more emphasis is placed on design procedures to minimize the possible overvoltages and control the sources of disturbances. An attempt has been made in this section to provide a balanced treatment of overvoltage protection in view of present-day concerns.

The subject of lightning and overvoltage protection is rather complex. A thorough treatment requires good understanding of many related subjects. First, the mechanisms by which lightning is generated and how its pertinent characteristics are related to power systems must be well understood. Second, the response of power systems to lightning and other causes of overvoltages must be studied. Analysis methods to study the phenomena are indispensable tools, which provide the basis for proper selection of design options. Invariably, overvoltages can be minimized, but they cannot be eliminated. As a result, power systems must be protected against overvoltages using overvoltage protection devices (surge arresters). In recent years, major breakthroughs have occurred in protective device technology. Effective protection requires a deep understanding of the capabilities of present technology as well as its limitations.

27.2 BASIC CONCEPTS AND DEFINITIONS

Electric power systems are subjected to external surges (lightning) as well as internally generated surges (switching), which may result in temporary high voltages. To maintain a highly reliable system, protection against these overvoltages is needed. This need is dictated by the fact that the insulation of power equipment (which may be air, oil, SF₆, etc.) is subjected to breakdown if sufficiently high voltage is applied. This protection involves a coordinated design of the power system itself and placement of proper protection devices at strategic locations for the purpose of suppressing overvoltages and avoiding or minimizing insulation failures.

Coordinated design involves
Effective grounding techniques
Use of shielding conductors
Preinsertion resistors during switching
Switching angle control among breaker poles
Use of surge capacitors

Protection devices include spark gaps and various designs of surge arresters.

The basic objective of overvoltage protection of power systems is to avoid insulation breakdown and associated outages or damage to equipment. The most common insulators used in power system apparatus and their characteristics are listed in Table 27-1.

In general, in terms of potential damage to equipment, the insulation of power apparatus can be classified into external and internal as follows:

- External insulation
 - Air
 - Porcelain
 - Glass
- Internal insulation
 - Oil
 - SF₆
 - Mica

The effects of external insulation breakdown are not as destructive as internal insulation breakdown. The reason is that external insulation is, in general, self-healing (self-restoring) after the cause of breakdown (overvoltage) ceases to exist. On the other hand, internal insulation breakdown generally results in permanent damage to the equipment and possibly catastrophic failure. These facts dictate different approaches for external and internal insulation protection. For external insulation protection, the objective is to minimize the expected number of insulation breakdowns subject to economic constraints. In this sense, many sophisticated approaches have been developed, which

TABLE 27-1 Common Insulators in Power Apparatus

Insulator	Breakdown, MV/m	Resistivity, $\Omega \cdot \text{m}$	Relative permittivity
Air	3	$\rho = \infty$	$\epsilon_r = 1$
Oil	10	$10^4 \times 10^{10}$	2.2
SF_6	15 at 1 atm 59 at 5 atm		
Mica	100	$10^{11} - 10^{15}$	4.5–7.5
Porcelain	10	3×10^{12}	5.7
Glass	...	10^{12}	4–7

balance system reliability (which is mainly related to insulation breakdowns) versus cost. Because many of the exogenous parameters, such as lightning strength and soil parameters are statistical in nature, the methodologies use statistical approaches. For internal insulation protection, deterministic methods are applied where the objective is to design for zero insulation breakdowns.

The above simplistic characterization of external and internal insulation is not always apparent in power apparatus. Specifically, the insulation of a specific power apparatus may be complex. For example, consider a transformer. The windings of the transformer may be submerged in oil (the dielectric is oil) while the terminals are exposed to air through the bushings (the dielectric is the air). When considering withstand capability of a power apparatus, we are not concerned with which dielectric will break first, although this is part of the design process. But rather we are concerned with the question of at what voltage the insulation (any part) will break down. Because insulation breakdown depends on voltage waveform as well as on some other factors, the following definitions, which have been taken from the ANSI Std C92.1, apply:

Withstand voltage. The voltage that electrical equipment is capable of withstanding without failure or disruptive discharge when tested under specified conditions.

Insulation level. An insulation strength expressed in terms of a withstand voltage (typically 10% less than the withstand voltage).

Transient insulation level (TIL). An insulation level expressed in terms of the crest value of the withstand voltage for a specified transient wave shape, for example, lightning or a switching impulse.

Lightning impulse insulation level. An insulation level expressed in terms of the crest value of a lightning impulse withstand voltage.

Switching impulse insulation level. An insulation level expressed in terms of the crest value of a switching impulse withstand voltage.

Basic lightning impulse insulation level (BIL). A specific insulation level expressed in terms of the crest value of a standard lightning impulse.

Basic switching impulse insulation level (BSL). A specific insulation level expressed in terms of the crest value of a standard switching impulse.

Note that two of the most commonly used measures, the basic lightning impulse insulation level and the basic switching impulse insulation level, are the most widely used values to characterize the insulation of power apparatus. Note that they are defined in terms of two specific waveforms: (1) the standard lightning impulse and (2) the standard switching impulse. The definitions of these waveforms are

Standard lightning impulse. A full impulse having a front time of $1.2 \mu\text{s}$ and a time to half value of $50 \mu\text{s}$. It is described as a 1.2/50 impulse. (See *American National Standard Measurement of Voltage in Dielectric Tests*, C68. 1.)

Standard switching impulse. A full impulse having a front time of $250 \mu\text{s}$ and a time to half value of $2500 \mu\text{s}$. It is described as a 250/2500 impulse. (See *American National Standard C68.1.*)

These waveforms are illustrated in Fig. 27-1.

The standard impulses were introduced because they remotely resemble lightning and switching waveforms, and they can be easily generated in a laboratory via an impulse generator. The basic structure of an impulse generator is illustrated in Fig. 27-2a. By stacking many basic structures together, one can create an impulse generator capable of generating an output impulse many million volts in crest.

The impulse voltage withstand of a power apparatus is strongly dependent on the duration of the impulse voltage. The time dependence is mainly due to the fact that arc generation involves an electron avalanche which takes a finite time to form. The full development of an arc across an insulator is classified as a breakdown. The time to breakdown is normally quantified with a volt-time characteristic. This characteristic can be determined by applying impulses across an insulator of increasing magnitude and recording the voltage and time at which breakdown occurred. For self-restoring insulation, this test is relatively simple and is illustrated in Fig. 27-3. In this way, volt-time curves for all insulators in usage have been determined. Unfortunately, the withstand voltage of non-self-restoring insulation cannot be readily determined without destroying the sample. This means that determining

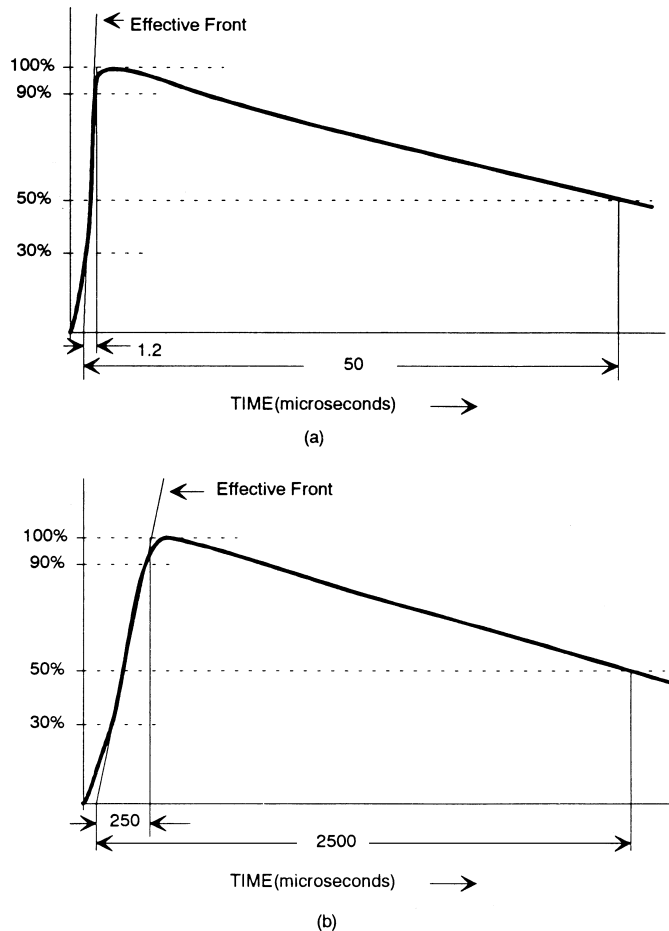


FIGURE 27-1 Standard waveform: (a) standard lightning impulse; (b) standard switching impulse.

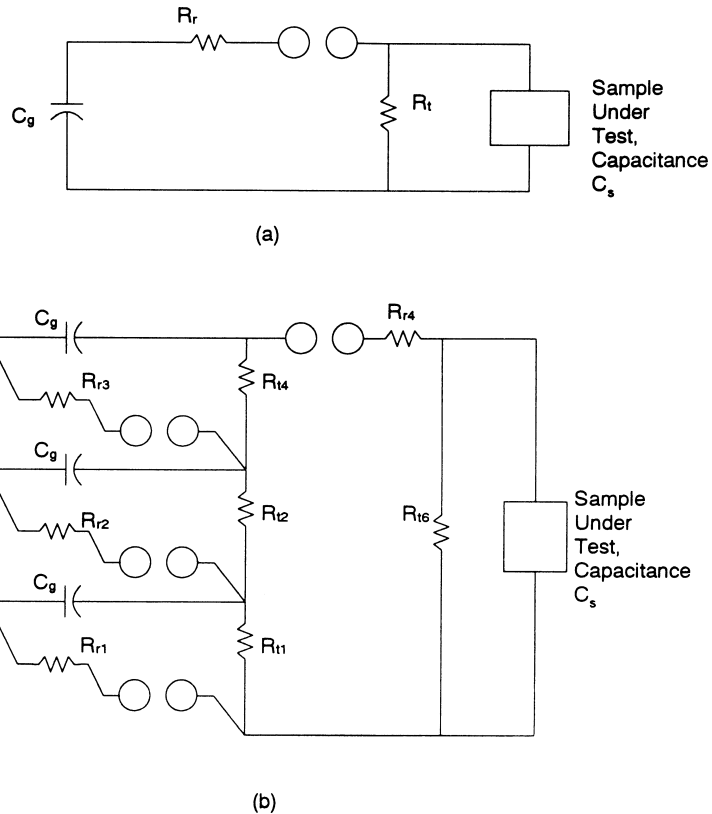


FIGURE 27-2 Impulse generator: (a) single-stage; (b) multiple-stage.

the volt-time curve of non-self-restoring insulation is a practical impossibility. For this reason, the methods for determining withstand voltage for internal insulation are different. Specifically, internal insulation is designed for a specific withstand capability, the *design withstand*. The manufacturer must guarantee a certain withstand at which the insulation, if tested, will not fail. This is the *tested withstand* and it is normally lower than the design withstand. Apparently, the *actual withstand* cannot be known without destroying the sample. The actual withstand is definitely higher than the tested withstand and probably higher than the design withstand.

There is another issue related to the fact that the withstand voltage depends on many other factors that exhibit random variations. Some of them are

- Insulation geometry and smoothness of surfaces
- Insulation contamination
- Atmospheric conditions
- Voltage polarity

It is a practical impossibility to quantify the effects of all variables on voltage withstand. For this reason, voltage withstand is described in statistical terms. In this sense, the following definitions apply with reference to Fig. 27-3:

Critical flashover (CFO) is the crest voltage of an applied impulse wave that will cause flashover on the tail of the wave 50% of the time and no flashover the other 50% of the time.

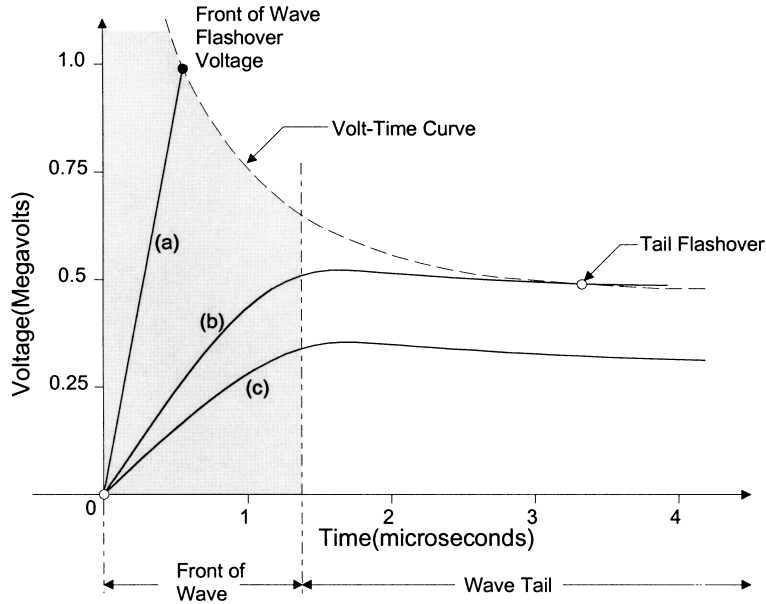


FIGURE 27-3 Determination of the volt-time curve of insulation breakdown.

Critical withstand is the highest crest voltage insulation can take without flashover under specified conditions—usually less than 1% probability of flashover.

Rated withstand is the crest voltage that insulation is required to withstand without flashover when tested by established standards under specified conditions (usually 5% to 10% less than critical withstand).

In summary, in this section we reviewed several basic concepts and definitions, which are useful in the process of designing protection systems.

27.3 MECHANISMS AND CHARACTERISTICS OF LIGHTNING

Introduction. Atmospheric electrical discharges known as *lightning* or *thunderbolts* (from cloud to cloud or cloud to ground) have captured the imagination and fear of the human race since ancient times. The ancient Greeks believed that lightning was Zeus' tool to punish human misbehavior or to demonstrate his anger. It was not until Benjamin Franklin that the first scientific inquiry occurred into the phenomenon of lightning. Since that time, lightning has been extensively studied and many theories have been developed, which reasonably explain the phenomenon. In addition to these theories, there exists an enormous amount of measured data of lightning characteristics. These data are useful for design of protection schemes against lightning.

This section presents a brief overview of the theory of thundercloud formation and lightning, the characteristics of lightning, and describes existing relevant data.

The Electrification of Thunderclouds. The cause of lightning is separation and accumulation of electrical charges in clouds via certain microphysical and macrophysical phenomena. This electrification

results in electric field intensities high enough to cause air breakdown and subsequent development of lightning. To explain these phenomena, certain theories have been developed. The most useful are the precipitation and convection theories and later improvements, most notably the charge-reversal temperature theory. Understanding of these theories is helpful in the design of protection systems against lightning. A brief description of the cloud electrification theories is provided in this section.

The precipitation theory, postulated as early as 1885 by physicists Elster and Geitel, is based on the observation that large water droplets accelerate toward ground because of gravity, while smaller water droplets (mist) remain suspended in air or rise as warmer air moves upward. Collisions between large water droplets and mist of water droplets and possibly ice crystals in the colder altitudes result in transfer of a net negative charge to the large water droplets. As they move toward lower altitudes (by gravity), they cause a net negative charge in the lower part of the cloud. Conservation of charge requires that the upper part of the cloud be positively charged, resulting in a dipole structure in the thundercloud. A simplified illustration of the process is given in Fig. 27-4.

The convection theory, which was formulated much later, is based on transfer of charged particles from one location of a cloud to another by the upward and downward drafts in the cloud. The theory suggests that the charged particles are generated by two mechanisms: (1) cosmic rays impinge on air molecules and ionize them, resulting in two ions, one positively charged, the other negatively charged; and (2) high-intensity electric fields around sharp objects on the earth's surface produce corona discharges, which result in positively charged ions. The positive ions are transported to higher altitudes by the upward draft in the cloud. On the other hand, the negative ions attach themselves to water droplets and ice particles, which move to lower altitudes due to gravity or downward drafts. The net result is a dipole structure in the thundercloud. A simplified illustration of the process is given in Fig. 27-5.

Precipitation and convection occur in a thundercloud simultaneously. Yet the two theories are distinct and independent. Both theories postulate that the thundercloud is a dipole with the negative pole near the earth, that is, negative dipole. Measurements made by Wilson and later by Simpson of the polarity of the dipole resulted in conflicting conclusions which generated debate and further research. Specifically, Wilson's measurements indicate that the thundercloud is a negative dipole (negative charge at the lower part of the cloud) while Simpson's measurements indicated a positive dipole. It took five decades of additional experimentation and measurements to resolve this apparent conflict. Today's most complete theory for lightning phenomena has established the fact that the structure of a thundercloud is *tripolar*, not bipolar. This structure allows the understanding of both Wilson's and Simpson's conclusions. Specifically, an electric tripole of the size of a thundercloud observed from a single specific point will appear as a dipole. Depending on the point of observation

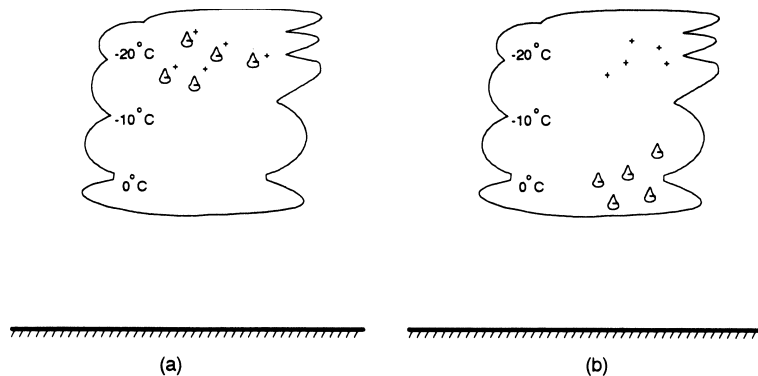


FIGURE 27-4 Illustration of the precipitation theory of cloud electrification: (a) separation of the charge due to collisions; (b) cloud electrification due to precipitation of charged water droplets.

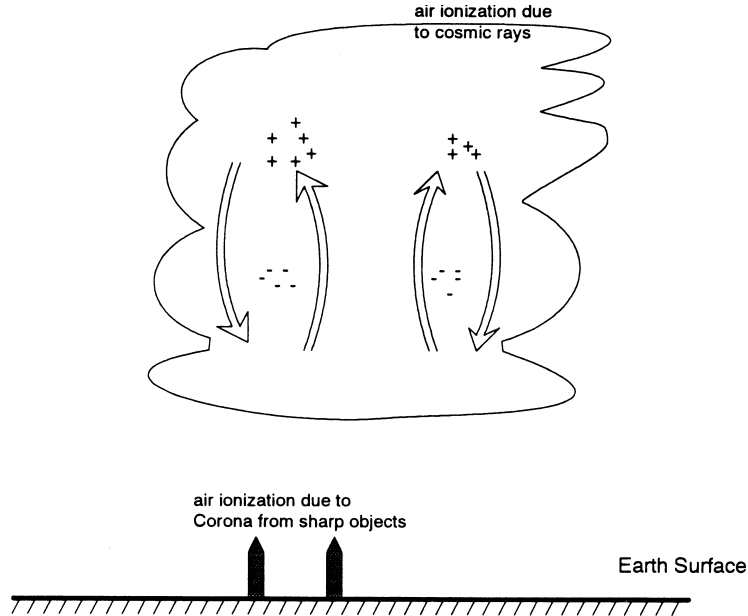


FIGURE 27-5 Illustration of the convection theory of cloud electrification.

one may conclude that it is a negative or positive dipole. Apparently, Wilson and Simpson made their measurements from different observation points. Their measurements were correct but because Wilson made the measurements from a distant point he concluded that the thundercloud is a negative dipole, while Simpson made his measurements from a point underneath the head of the cloud and concluded that the thundercloud is a positive dipole.

Both theories, precipitation and convection, do not completely explain all phenomena occurring in a thundercloud. For example, it has been observed from studies that larger droplets, when they break, acquire positive charge on aggregate. This leads to the hypothesis that the positive charge is due to large droplets that break as they accelerate toward ground. However, this hypothesis is not totally true because it does not explain the fact that precipitation particles below the negative charge carry much greater positive charge than those produced by the droplet fragmentation process. Another hypothesis was based on ice particles accelerating toward ground—as the ice particles reach lower altitudes, they melt and tend to acquire positive charges, which explains the existence of positive charge at altitudes below 4 km. However, this hypothesis still does not explain the existence of positive charges at higher altitudes.

Recent measurements and observations in the past three decades resulted in another hypothesis which explains the tripole nature of a thundercloud. This is the so-called charge-reversal hypothesis, which states that when graupel particles collide with ice crystals, the charge transferred to a graupel particle is dependent on the temperature. At temperatures above a certain value, which is called the *charge-reversal temperature*, the transferred charge is positive. The exact value of the charge-reversal temperature is being debated, but it is believed to be around -15°C . The process is illustrated in Fig. 27-6 in a simplified manner. Considering the fact that the temperature of the atmosphere is -15°C at an approximate altitude of 6 km, this means that due to collisions of graupel particles and ice crystals, the thundercloud will be, on aggregate, negatively charged for altitudes above 6 km and positively charged below 6 km. The situation is illustrated in Fig. 27-7. This hypothesis has been verified in the laboratory and explains the levels of negative and positive charges in a thundercloud. Yet, the exact microphysics of this phenomenon are practically unknown.

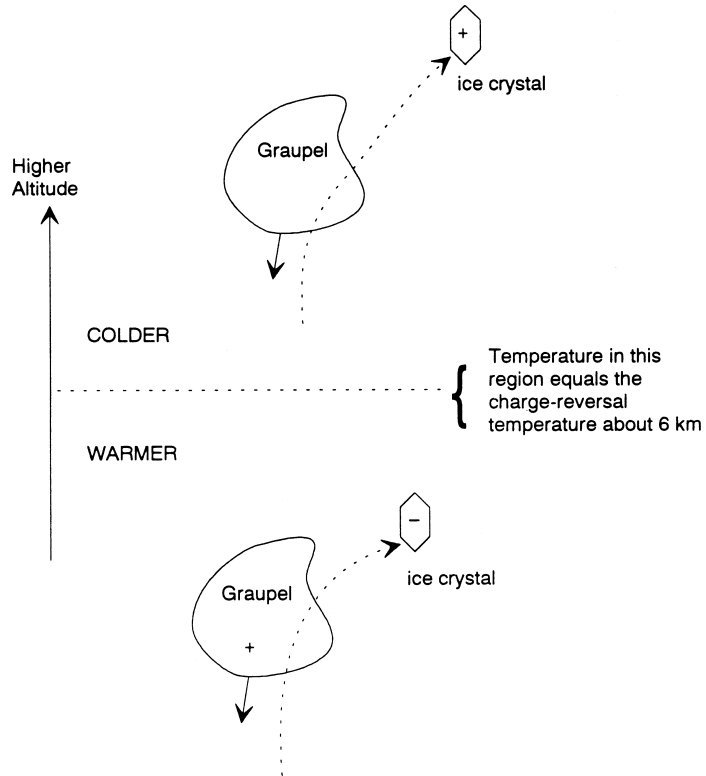


FIGURE 27-6 Explanation of the charge-reversal temperature theory.

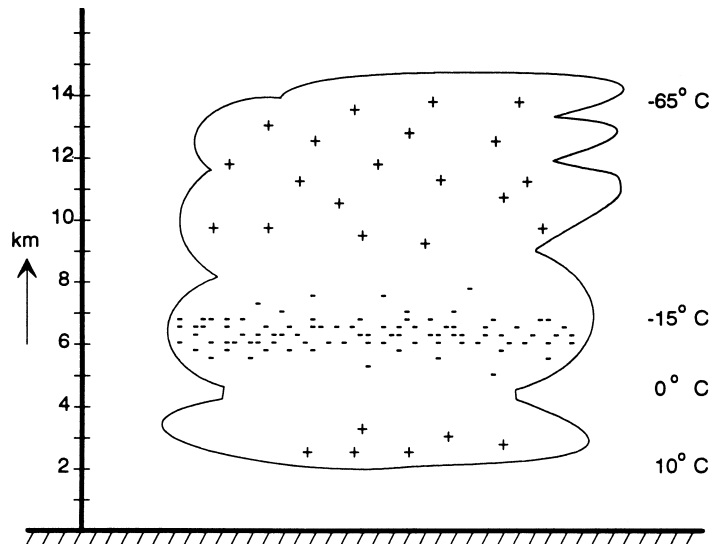


FIGURE 27-7 An electrified thundercloud is typically tripolar.

In summary, the precipitation model with the graupel—ice crystal interaction and charge-reversal temperature best explains most of the behavior of a thundercloud. Yet this model totally ignores the forceful upward and downward drafts within a thundercloud. The convection model considers these drafts but it is unable to explain certain observed phenomena in a thundercloud. Perhaps one day a theory will be developed, which combines the precipitation and convection models and completely accounts for all phenomena related to the electrification of a thundercloud. What has been verified with measurements are the following facts: a thundercloud can be electrified in such a way that positive charge accumulates at the top of the cloud and negative, at the lower part of cloud. A smaller positive charge may be present at lower altitudes of a thundercloud. These charges are responsible for lightning. The mechanism of lightning is explained next.

Mechanisms of Lightning. Lightning initiates whenever the charge accumulation in a thundercloud is such that the electric field between charge centers inside the cloud or between cloud and earth is very high. For power engineering purposes, only cloud-to-earth lightning strokes (ground flashes) are of importance and will be discussed next. An electrified thundercloud will generate an electric field in the space between the cloud and earth as is illustrated in Fig. 27-8. When the intensity of this field is high enough, a discharge will initiate. Typically, the process involves three phases. In the first phase, the high electric field intensity may generate local ionization and electric discharges, which are known as *pilot streamers*. A pilot streamer is followed by the so-called *stepped leader*. The stepped leader is a sequence of electric discharges, which are luminous; they propagate with a speed approximately 15% to 20% of the speed of light, and they are discrete, progressing approximately 50 m at a time. The time between *steps* is few microseconds to several tens of

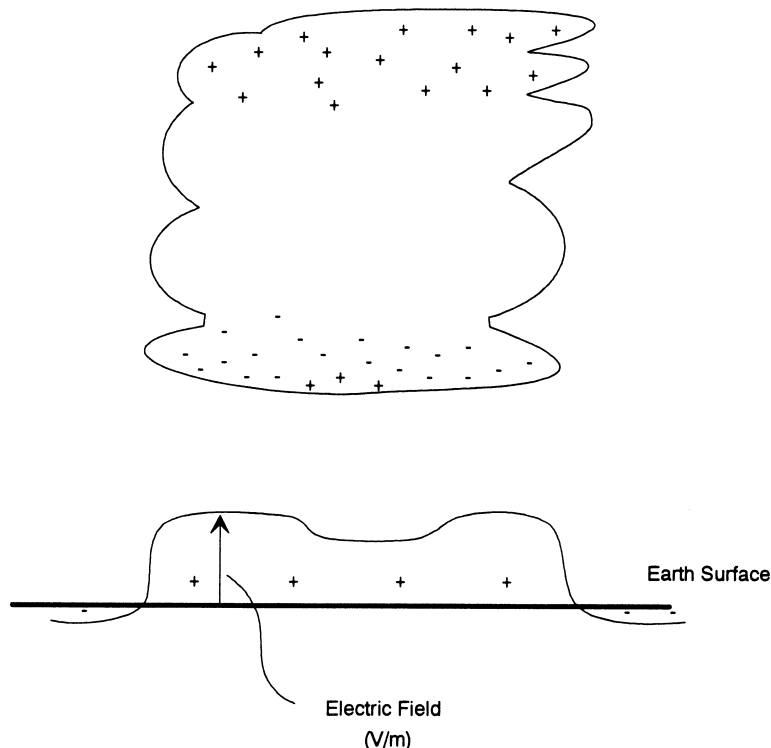


FIGURE 27-8 Illustration of electric field below an electrified thundercloud.

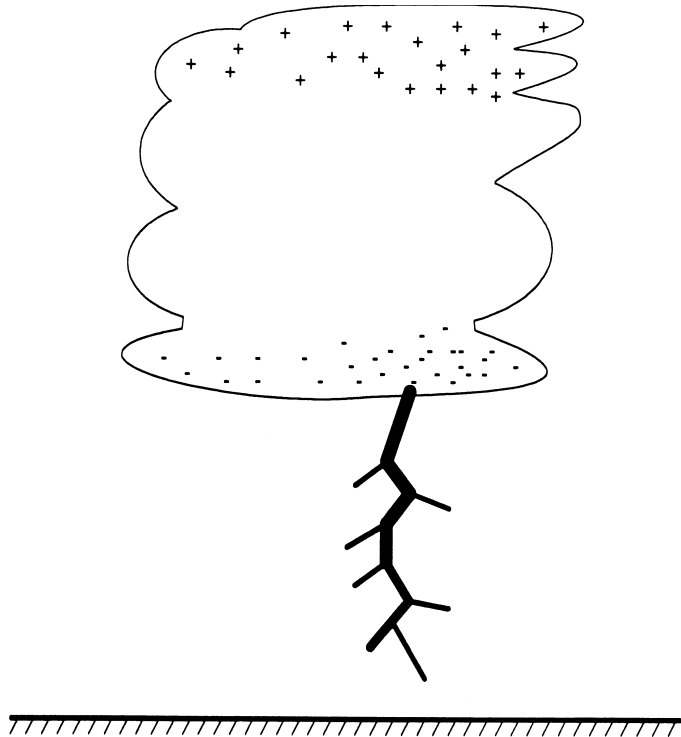


FIGURE 27-9 Illustration of stepped-leader development.

microseconds. A pictorial view of the stepped leader development is shown in Fig. 27-9. The stepped leader will eventually reach the surface of the earth and will strike an object on the earth. However, where it will strike is not determined until the stepped leader is within a *striking distance* from the object. A model for the striking distance will be described in Sec. 27.7. It is possible that a stepped leader or multiple stepped leaders may also initiate from an object on the surface of the earth. In this case, the two stepped leaders may meet at some point. There is also evidence that the initial stepped leader may originate from a tall structure on the earth and not from the cloud.

The second phase initiates when the stepped leader reaches an object on the earth or meets an upward moving stepped leader. Specifically, a high-intensity discharge occurs through the channel established by the stepped leader. This discharge is extremely luminous and therefore visible. It propagates with a speed of about 10% to 50% of the speed of light. The development of the return stroke is illustrated in Fig. 27-10. The return stroke carries an electric current of anywhere from few thousands of amperes to 200 thousands of amperes. The current magnitude rises fast, within 1 to 10 μs , to the peak value and then decreases rapidly. The discharge is known as the *return stroke* or simply the *lightning stroke*. The return stroke transfers a substantial amount of positive charge from the earth to the cloud and specifically to the charge center where the lightning was originated. This transfer results in a significant lowering of the potential of the charge center. This phenomenon initiates the third phase of lightning. In this phase, discharges may occur from other charge centers within the thundercloud to the depleted charge center because of the increased potential difference between them. This discharge will trigger another stroke between cloud and ground through the already established conductive channel with the first stroke. This process may be repeated several times, depending on the electrification status of the thundercloud, resulting in multiple strokes. There is evidence

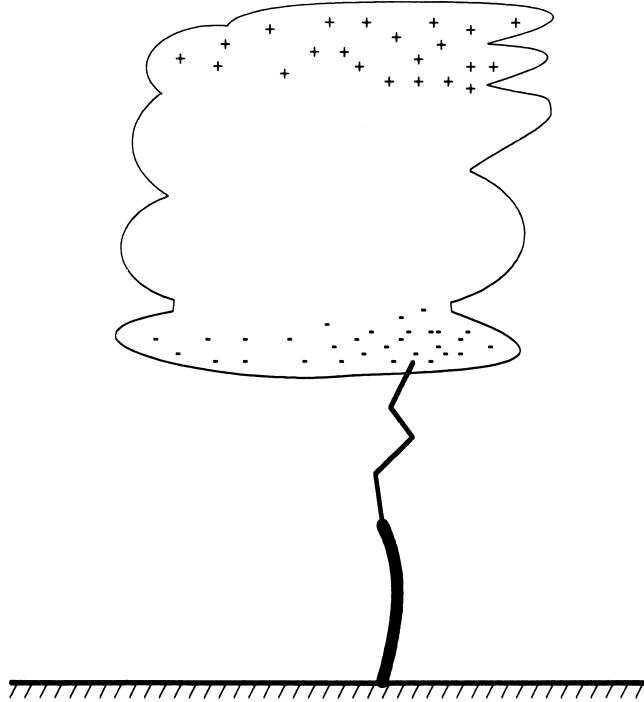


FIGURE 27-10 Illustration of return-stroke development.

that most lightning to ground involves multiple strokes. For example, an analysis of 1430 strokes to the earth by Anderson (1968) resulted in the following statistics:

Single-stroke lightning	36%
Lightning involving six or more strokes	21%
Mean value of multiple strokes	3

It should be mentioned, however, that positive polarity lightning is typically single stroke. Extreme cases have been recorded with a large number of multiple strokes such as 40 or 50 with duration of the entire lightning event approaching 1 s. For example, a 40-stroke lightning event, which lasted 0.624 s is on record. The time interval between successive strokes may be in the order of few milliseconds. However, there is evidence that sometimes the multiple strokes may be so smooth as to appear as a continuous lightning current. This occurs because as long as there is a conductive path between the cloud and ground, electric current will flow until the cloud is neutralized enough for the conductive path to interrupt. The continuous flow of lightning current can be destructive because of its long duration even if the magnitude may be much lower than the crest of a stroke.

Characteristics of Lightning Strokes. The parameters of lightning ground strokes are very important in the design of protection schemes against lightning. The most important parameters are

- Voltage
- Electric current
- Waveform
- Frequency of occurrence

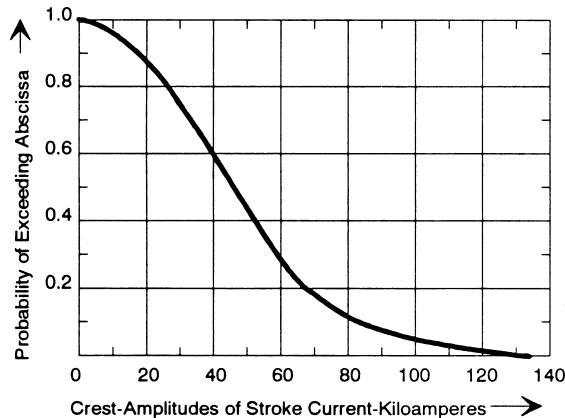


FIGURE 27-11 Distribution of lightning current magnitudes [recorded by Berger (1967) at Mount San Salvatore].

The voltage between a thundercloud and the earth prior to a ground stroke has been estimated from 10 to 1000 MV. For design work, however, the protection engineer is interested in the voltage appearing on the stricken power apparatus. This voltage will be equal to the product of the impedance times the stroke current.

It is generally accepted that the ground-stroke current is independent from the terminating impedance. The reason is that the terminating impedance is much lower than the resistance of the lightning discharge channel, which is on the order of few thousand ohms. Thus, a ground stroke is normally considered as an ideal current source at the point of strike. The crest of the stroke electric current can vary over a wide range: 1 to 200 kA. Data on ground-stroke current magnitudes have been collected by many researchers. Among those, the work of Berger (1967) at Mount San Salvatore in Switzerland has been widely accepted. Statistical representation of these data is shown in Fig. 27-11.

The waveform of the lightning ground stroke current, and especially the rise time, is very important. Again, statistical representation of stroke current rise times data collected by Berger is given in Fig. 27-12.

The frequency of occurrence is also a very important parameter. In order to quantify lightning activity, the crude measure of *thunderstorm day* has been introduced. A thunderstorm day is defined as a 24-h period in which at least one thunder clap has been heard. Collection of historical thunderstorm activity data by the National Weather Service resulted in maps of equi-thunderstorm-day contours. These maps are known as isokeraunic maps, from the Greek word *keraunos*, lightning. Such a map is illustrated in Fig. 27-13. It is important to note that this map, by definition, provides only a crude measure of lightning activity. Specifically, by definition, a thunderstorm day does not provide any information on the frequency of and total lightning activity. Yet, because of lack of better data, the isokeraunic maps have been used for estimation of lightning activity in an area. There are several models, which provide the approximate number

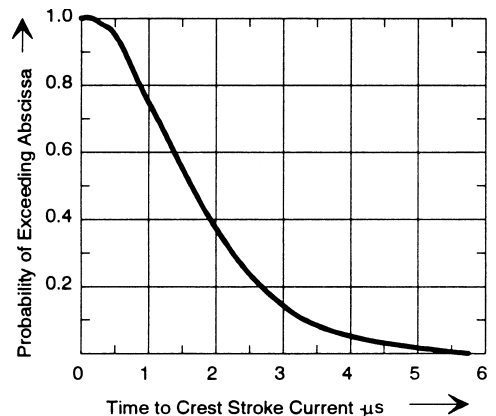


FIGURE 27-12 Distribution of lightning current rise times [recorded by Berger (1967) at Mount San Salvatore].

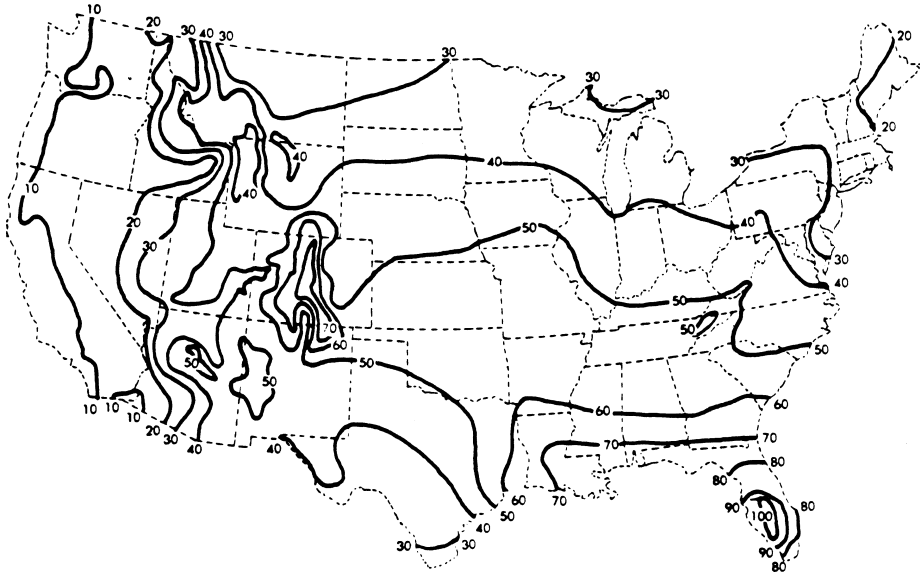


FIGURE 27-13 Isokeraunic curves for the continental United States.

of cloud-to-ground lightning per unit of area as a function of the isokeraunic level. These models will be discussed in detail in Sec. 27.7. As an example, Anderson (1975) has suggested the following

$$N_1 = 0.12T$$

where N_1 is the ground flash density per square kilometer per year and T is the number of thunderstorm days.

Early in the 1980s, the Electric Power Research Institute sponsored a project at the State University of New York at Albany (SUNYA) which resulted in the National Lightning Detection Network (NLDN) records. The system integrated two networks and basically records cloud-to-ground lightning discharges. The objective of the project was to collect lightning data over a period of 10 years, which could be used for lightning protection of power systems. Figure 27-14 illustrates average lightning flashes per square kilometer for the state of Florida. The data were collected over a 5-year period (1985 to 1989). Note that these data correlate reasonably well with the isokeraunic maps data of Fig. 27-13. Similar systems have been installed in many countries.

Summary. This section has described the mechanism of thundercloud formation and electrification and the initiation, mechanism, and characteristics of lightning. Finally, statistical data on lightning parameters were presented. These data are useful for design work.

27.4 POWER SYSTEM OVERVOLTAGES

The causes of power system overvoltages are numerous and the waveforms are complex. It is customary to classify the transients on the basis of frequency content of the waveforms. In this sense, the following three broad categories are defined:

- Power frequency overvoltages
- Switching overvoltages
- Lightning overvoltages

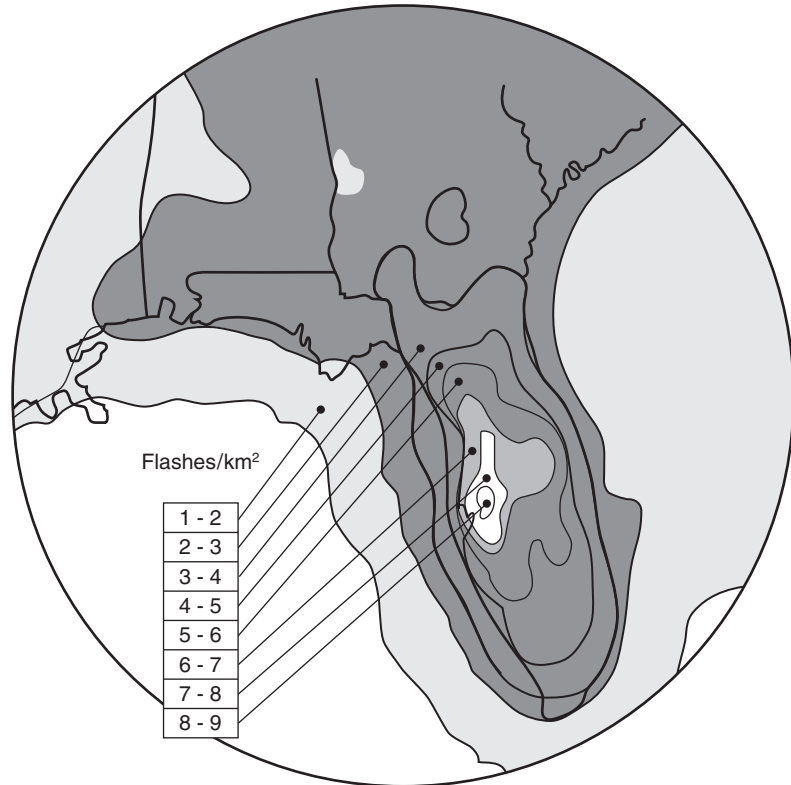


FIGURE 27-14 Average annual flash density data from 1985 to 1989. (*Electric Power Research Institute.*)

Table 27-2 provides brief descriptions and typical causes of the most commonly encountered overvoltages in power systems. The relative level of overvoltages due to these causes is illustrated in Fig. 27-15.

In designing a well-protected electric power system, it is extremely important to thoroughly understand the types, frequency, and magnitude of the expected overvoltages on the power system. For this reason, this section provides a concise discussion of the nature, generation mechanisms, and characteristics of power frequency, switching, and lightning overvoltages in power systems.

Power Frequency Overvoltages. The magnitude of power frequency overvoltages is typically low compared to switching or lightning overvoltages. Specifically, for most causes of these types of overvoltage, the magnitude may be few percent to 50% above the nominal operating voltage. However, they play an important role in the application of overvoltage protection devices. The reason is that modern overvoltage protection devices are not capable of discharging high levels of energy associated with power frequency overvoltages. Thus, it is imperative that protective device ratings be selected in such a way that they do not operate under any foreseeable power frequency overvoltages.

The most common causes of power frequency overvoltages are (1) electric faults, (2) sudden changes of load, and (3) ferroresonance. An electric fault results in voltage collapse for the faulted phase and in a possible overvoltage at the unfaulted phases. The magnitude of the overvoltage depends on the parameters of the circuit, such as positive, negative, and zero sequence impedance, as well as the grounding parameters of the system, such as ground impedance or single- or multiple-grounded

TABLE 27-2 Power-System Overvoltages

Category	Description	Causes
Power frequency overvoltages	Temporary overvoltages dominated by the power frequency component	Electric faults Sudden changes of load Ferroresonance
Switching overvoltages	Temporary overvoltages resulting from a switching operation	Energization of lines Deenergization of capacitor banks Fault interruption/TRV High-speed reclosing
Lightning overvoltages	Temporary overvoltages resulting from a lightning stroke terminating at a phase conductor, shield conductor, any other part of a power system, or a nearby object (tree, etc.)	Energization/deenergization of transformers Other Lightning—cloud-to-ground flashes

system. Figure 27-16 illustrates a typical case of a single-phase-to-ground fault at the end of a 40-mi-long 115-kV transmission line. Because the electric power system is not completely symmetric, the magnitude of the overvoltage on the unfaulted phases may be different; that is, for the case of Fig. 27-16, the overvoltage on phase B is 28.3%, while for phase C the overvoltage is 31.9%. Many studies have

Power frequency overvoltages
Switching overvoltages
Lightning overvoltages

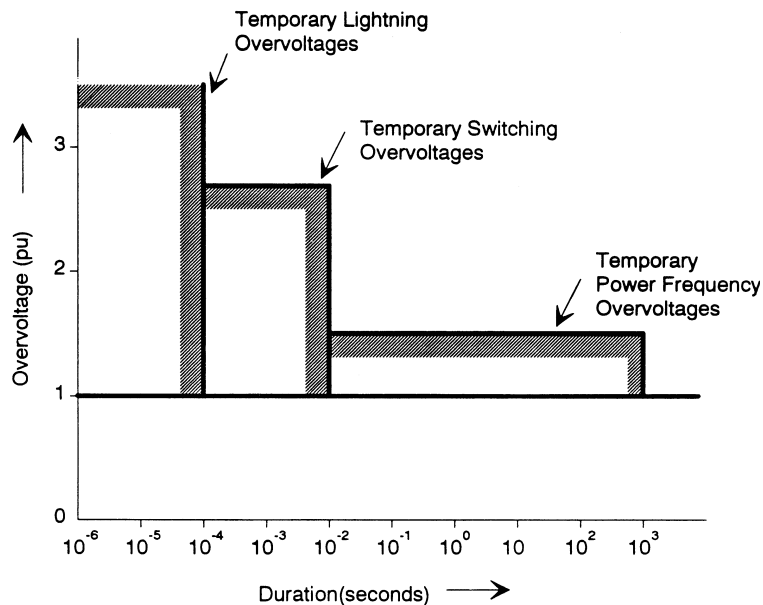


FIGURE 27-15 Typical range of magnitude and duration of power system temporary overvoltages. [From Regaller (1980).]

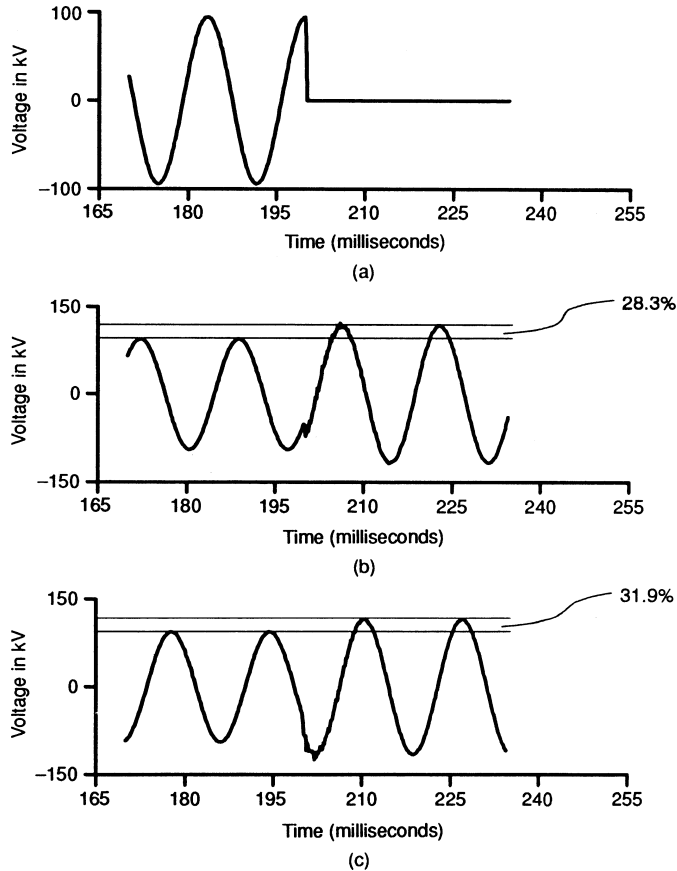


FIGURE 27-16 Overvoltage due to a single-phase-to-ground fault at the end of a 40-mi-long 115-kV line: (a) phase A voltage; (b) phase B voltage; (c) phase C voltage.

been performed over the years to determine simple techniques for determining the power frequency overvoltages. As a first approximation, one can determine the power frequency overvoltage due to a fault from the sequence parameters (positive-, negative-, and zero-sequence impedances) at the fault location. Figure 27-17, taken from Johnson (1979), illustrates the power frequency overvoltage at the unfaulted phases due to a ground fault in one phase as a function of the ratios (X_0/X_1) and (R_0/X_1) .

Computer models for determining the power frequency overvoltage by taking into consideration all relevant factors have been developed. Using these models, one can determine the exact power frequency overvoltage and the effect of grounding practices. As an example, Fig. 27-18, taken from Mancao et al. (1992), illustrates the maximum line-to-ground overvoltage, per unit (pu), on typical distribution circuits versus fault distance from the feeding substation.

Another source of power frequency overvoltages is the so-called Ferranti effect, which occurs when a load is disconnected at the end of a long transmission line. In this case, the line draws a capacitive current from the source, which generates a voltage gradient along the line of such a phase as to increase the voltage at the open end of the line. An approximate expression of the overvoltage at the open end of the line is given by

$$\text{Overvoltage in pu} = \frac{1.0}{\cos(\beta l)}$$

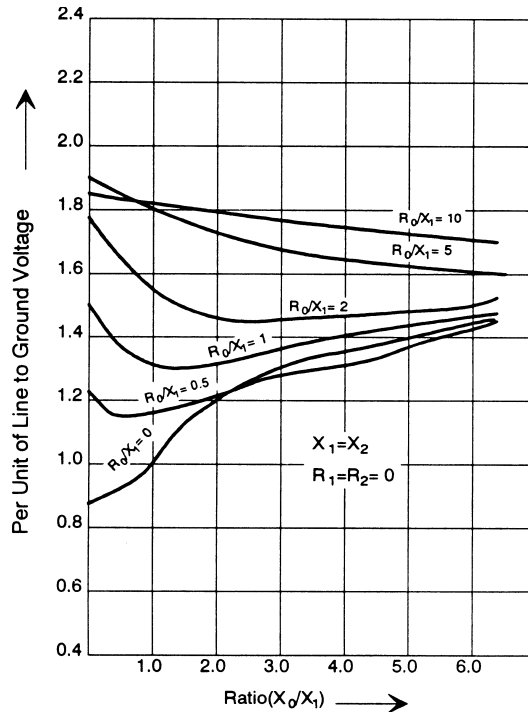


FIGURE 27-17 Overvoltage on unfaulted phase during single-line-to-ground fault. [From Johnson (1979).]

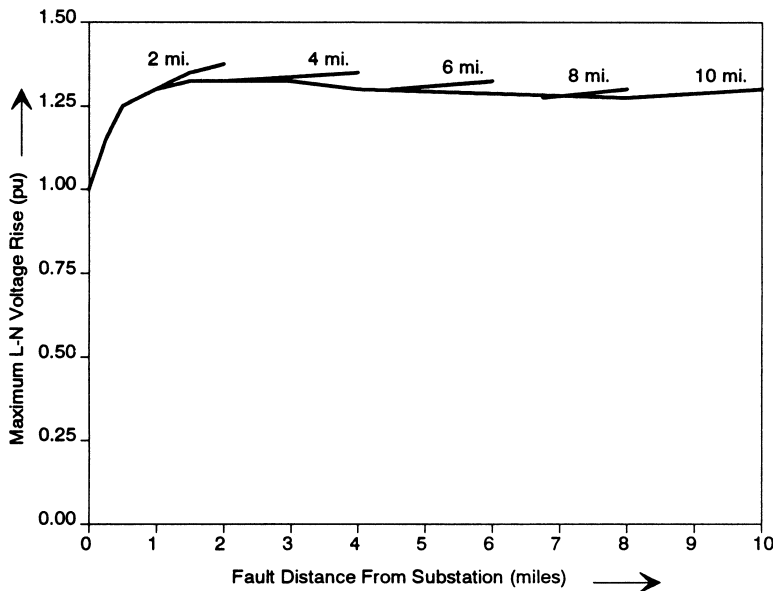


FIGURE 27-18 Overvoltage on unfaulted phases of a distribution circuit as a function of fault distance and circuit length. [From Mancao et al. (1992).]

where β is the propagation characteristic of the line ($\omega\sqrt{LC}$) and l is the total length of the line. A typical transmission line of 400 mi may experience an overvoltage of 1.30 pu when one end of the line is open.

Ferroresonance is another cause of power frequency overvoltages but is less frequent. Ferroresonance may occur when energizing long transmission lines and unloaded power transformers, in single-phase switching of a 3-phase transformer, and in other cases involving an iron-core magnetic circuit connected to a substantially capacitive circuit. The overvoltages resulting from ferroresonance can be serious and especially destructive to gapless arresters present in the system. As an example, Fig. 27-19, taken from an IEEE committee report, illustrates the maximum overvoltage due to ferroresonance involving single- or double-phase switching of a 3-phase transformer with an ungrounded primary (delta or wye). The severity of ferroresonance depends on the amount of capacitive reactance present in the system.

Other causes of power frequency overvoltages are (1) generator speedup due to load rejection, (2) generator self-excitation, and (3) malfunction of regulating equipment.

Switching. Switchings in a power system occur frequently. A variety of switchings are performed for routine operations or automatically by control and protection systems. Typical switchings are as follows:

- Lines (transmission or distribution)
- Cables
- Shunt/series capacitors
- Shunt reactors
- Transformers
- Generators/motors

Another class of switching transients are those generated from *insulation flashovers* and breaker *restrikes*. These phenomena are equivalent to the closing of a switch and generate switching surges, which propagate in the system.

Overvoltages resulting from switching operations are typically proportional to the power frequency voltage. For example, energization of a 3-phase line can result in an overvoltage at the open end, which can be as high as 5 pu, depending on the timing of switching with respect to the source. The frequency

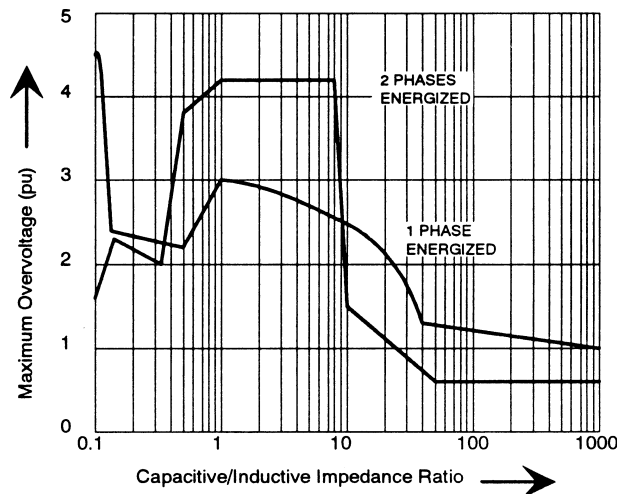


FIGURE 27-19 Maximum overvoltage due to ferroresonance triggered by single- or double-phase switching of a 3-phase transformer with an ungrounded primary.

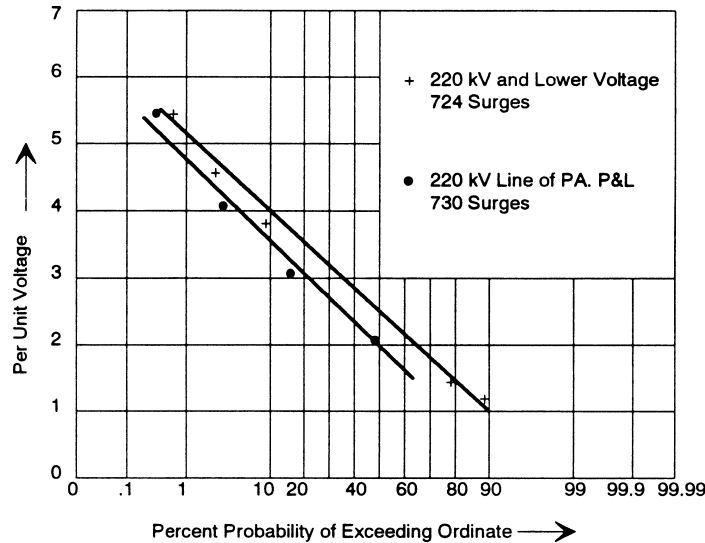


FIGURE 27-20 Probability distribution curves of measured switching overvoltages. [From Johnson (1979).]

content of switching transients depends on system parameters. As an example, Fig. 27-20, taken from Johnson (1979), illustrates probability distribution curves of measured line switching overvoltages. Note that there is a substantial probability for overvoltages higher than 5.0 pu.

Switching transients for extra-high-voltage systems, that is, 230 kV and above, can be quite high and must be controlled to avoid the need for higher insulation. There are two methods for controlling the magnitude of switching overvoltages: (1) using breakers with resistor preinsertion and (2) using opening resistors or wound-type potential transformers to discharge trapped charge on lines.

Breakers with resistor preinsertion place a resistor between source and line under energization for a short duration (e.g., 0.8 ms) prior to a direct connection of the source to the line. Proper selection of resistor values and insertion time enables effective control of maximum switching overvoltages. As an example, Fig. 27-21 illustrates the probability distribution curve of switching overvoltages when a resistor preinsertion breaker is used. Note that the maximum switching overvoltage is below 2.5 pu.

Trapped charge on a transmission line can cause excessive switching overvoltages (for specific timing of line energization with respect to source phase). In addition, trapped charge can cause breaker restrike because it contributes to overstressing the breaker insulation. Wound-type potential transformers or opening resistors provide a mechanism for quick drainage of trapped charge on lines.

Switchings can cause other undesirable effects such as inrush currents in transformers and ferroresonance, which has already been discussed.

Lightning Overvoltages. Electric power systems are exposed to weather and therefore are subjected to lightning strikes, which result in overvoltages. Lightning overvoltages are generated by direct lightning strikes on a power system apparatus or indirect strikes to nearby objects, from which subsequent overvoltage is transferred to the system via inductive, capacitive, and conductive coupling.

Unlike power frequency overvoltages and switching overvoltages, which are proportional to the system voltage, lightning overvoltages are independent of system voltage but depend on system impedances. For example, a direct lightning hit to a phase conductor of an overhead transmission line will generate an overvoltage proportional to the characteristic impedance of the line and proportional to the current magnitude of the lightning stroke. This overvoltage may be several million volts. It is a practical and economical impossibility to insulate distribution or lower-kilovolt-level

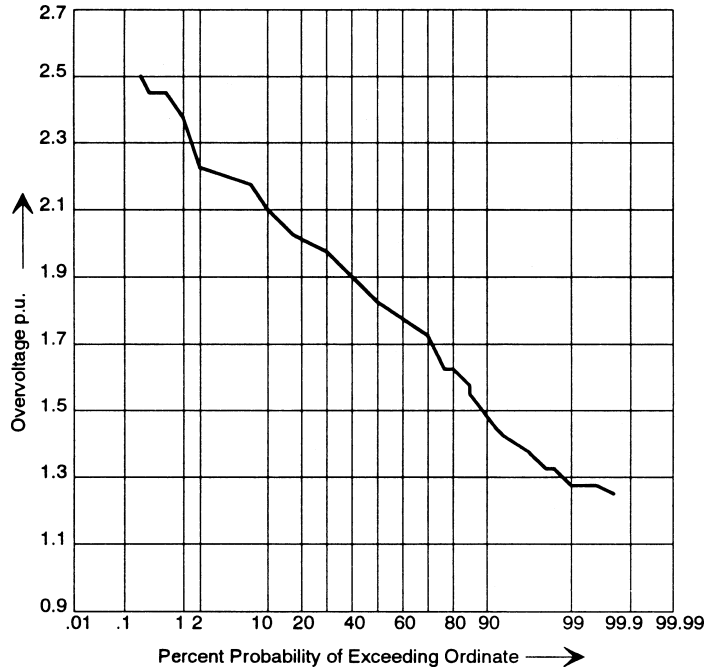


FIGURE 27-21 Probability distribution curves of computed switching overvoltages (switching with a resistor preinsertion breaker).

transmission lines (i.e., 230 kV and below) to withstand this type of overvoltage. As will be discussed in Sec. 27.7, a coordinated design procedure is applied to minimize the effects of lightning; this procedure involves among other things: (1) shielding of lines and equipment, (2) effective grounding, and (3) application of protective devices (surge arresters). The presence of the shielding system ensures that lightning, which otherwise will terminate to a phase conductor, will terminate on a wire, terminal, etc., which is electrically connected to the grounding system. A well-designed grounding system will divert the majority of the lightning stroke current into the soil and thus will minimize the destructive lightning overvoltages. The subject will be further discussed later. Here, a typical example of lightning overvoltages on a 115-kV shielded line is shown in Fig. 27-22. The figure shows the overvoltage at the top of the tower, voltage across insulator of phase A, and the ground potential rise at the tower base. The voltages are given in kilovolts per kiloampere of lightning stroke current. The case shown is for a relatively short tower with effective grounding. The figure shows the effects of nearby towers, which generate reflections of the lightning surge with the end effect of quickly reducing the lightning overvoltages. It should be apparent that the tower-grounding system plays an important role in determining the magnitude of lightning overvoltages, as illustrated in Fig. 27-23. The topic of grounding will be further discussed later.

Lightning strokes to nearby trees, ground, or other objects can result in voltage surges into the power system through coupling. The coupling can be conductive through the conductive soil and the power system grounding structures, inductive, or capacitive. In a typical situation, all the coupling mechanisms may be present, resulting in a voltage surge to the power system. These voltages are called *induced voltage surges* and are generally much lower than those occurring after a direct strike. Specifically, they rarely exceed 400 kV. The induced lightning overvoltages are of concern for distribution lines 35 kV or below. Higher-kilovolt-level lines (i.e., 69 kV and above) have sufficient insulation withstand so that induced lightning voltages do not present the risk of flashover.

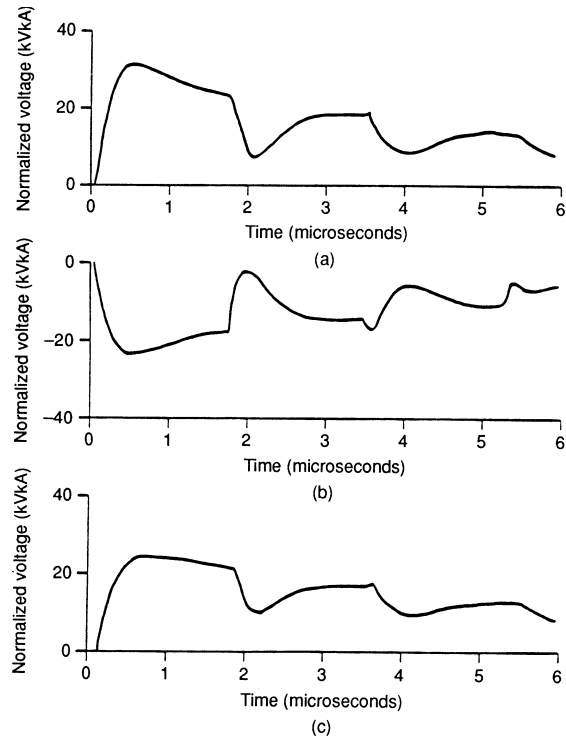


FIGURE 27-22 Typical lightning overvoltages on a transmission line: (a) top of tower voltage; (b) voltage across insulator (phase A); (c) tower ground potential rise. [From Meliopoulos (1988).]

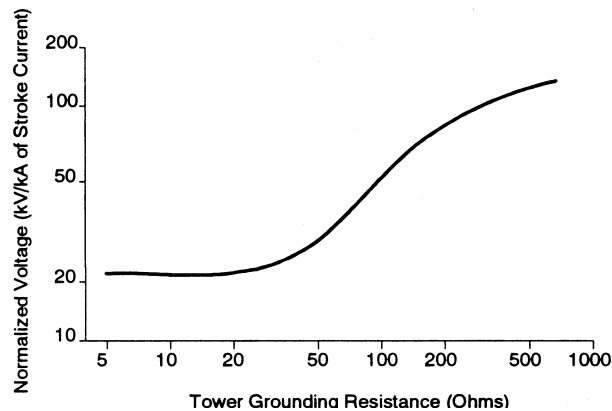


FIGURE 27-23 Effects of tower footing resistance on a specific 115-kV transmission line (standard lightning wave = $1.2/50 \text{ ms}^{-1}$). [From Meliopoulos (1988).]

27.5 ANALYSIS METHODS

Design of overvoltage protection systems requires a thorough understanding and analysis of transient overvoltages in power systems. Over the years, many analysis methods have been developed for this purpose. All analysis methods require a proper model of the system under study. In this section, we shall discuss modeling requirements for transient analysis and various analysis methods.

Modeling is probably the most important task in a study. There are many modeling choices which must be made in a prudent way and in view of the objectives of the study. Modeling choices are affected by

Phenomenon under study

Period of concern

Model selection of individual system components

For overvoltage analysis, typical phenomena under study will be line switching, capacitor bank switching, and lightning. The period of concern may be seconds, milliseconds, or microseconds. Model selection of individual system components should be guided by the expected frequency content of the transient. The selected models should have the proper frequency response required for the study under consideration. There is a large number of components to be modeled. A representative list is given in Table 27-3.

Two other related issues are (1) what to model and (2) how to model. The types of choices to be made regarding the question of what to model may include (1) bus inductance, (2) bus capacitance, (3) transformer winding capacitance, and (4) separation distance between arrester and transformer. The question of how to model is complicated. Typical choices are illustrated in Table 27-4. The task of component model selection is very important. To illustrate the point, consider a 40-mi-long transmission line. The line can be represented as a distributed-parameter model or a lumped-parameter model consisting of a set of cascaded pi sections. Figure 27-24 illustrates the switching voltages computed for this line by using the two models. Note that the solutions are different. Of course, the distributed-parameter model provides the correct answer. Examples of simplified lumped-parameter models and distributed-parameter models are illustrated in Fig. 27-25.

TABLE 27-3 A Representative List of Power-System Components

Transmission lines
Single-phase
Three-phase
Overhead
Underground
Lumped capacitors
Iron-core transformers
Generators
Surge arresters
Grounding
Switches, fuses, etc.

TABLE 27-4 Typical Model Choices for Components

Component description	Mathematical model
Lumped-parameter model	Ordinary differential equations
Resistors	
Capacitors	
Inductors	
Distributed-parameter model	Partial differential equations
Lines	
Buses	
Iron-core transformers	Nonlinear equations
Surge arresters	Nonlinear/time-varying equations
Circuit-breaker operator	Logical equations

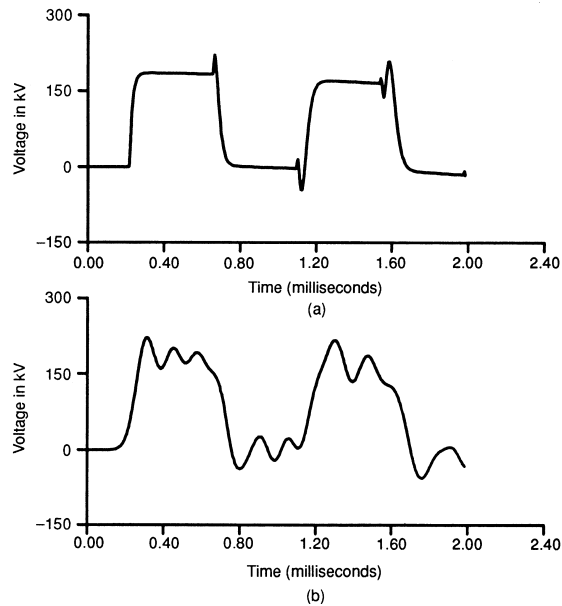


FIGURE 27-24 Switching overvoltage at the open end of a 40-mi-long 115-kV line: (a) distributed-parameter model; (b) model with six cascaded pi sections.

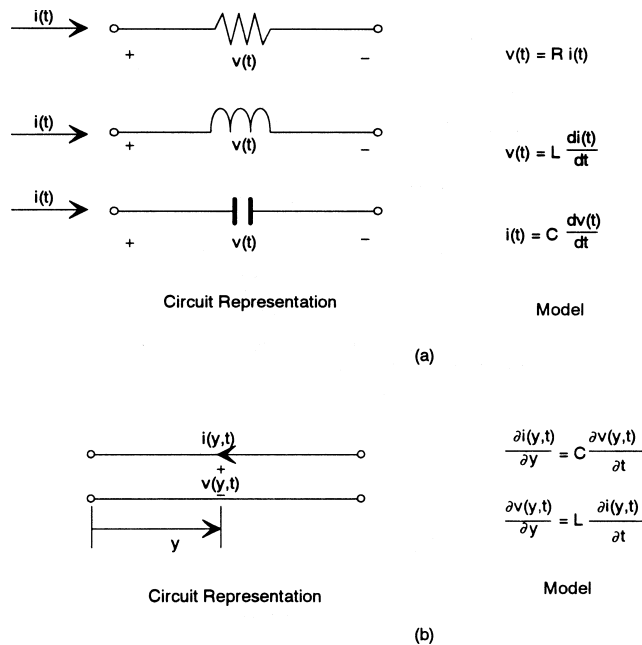


FIGURE 27-25 Power system models for transient analysis: (a) lumped-parameter models; (b) distributed-parameter models. [From Meliopoulos (1988).]

Once the model has been selected, analysis can determine the transient overvoltages for a specific event. Analysis methods can be classified into three categories:

- Graphical methods
- Analytical methods
- Numerical methods

Graphical Methods. The graphical method is based on the observation that the solution for transient voltages and currents in a transmission line can be represented with traveling waves along the line. Under the assumption of an ideal transmission line (zero losses and constant inductance and capacitance per unit length), the waves travel along a line without distortion. Figure 27-26 illustrates the general solution in this sense. Waves are altered when they reach a discontinuity. Specifically, at discontinuity, a wave will be partially reflected and partially transmitted. If the discontinuity involves only resistive elements, the coefficients of reflection and transmission will be constant. This situation is illustrated in Fig. 27-27. The basic relationship among incident (subscript i), reflected (subscript r), and transmitted (subscript t) waves are as follows:

Reflected wave:

$$\begin{aligned} E_r &= \alpha E_i \\ I_r &= -\alpha I_i \\ \alpha &= \frac{Z_{eq} - Z_{01}}{Z_{eq} + Z_{01}} \quad (\text{reflection coefficient}) \\ Z_{eq} &= \frac{R_L Z_{02}}{R_L + Z_{02}} \end{aligned}$$

Transmitted wave:

$$\begin{aligned} E_t &= \delta E_i \\ I_t &= \delta \frac{Z_{01}}{Z_{02}} I_i \\ \delta &= \frac{2Z_{eq}}{Z_{eq} + Z_{01}} \quad (\text{transmission coefficient}) \end{aligned}$$

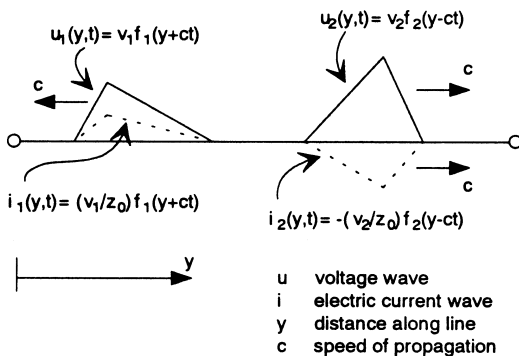


FIGURE 27-26 General wave solution for an ideal distributed-parameter single-phase transmission line.

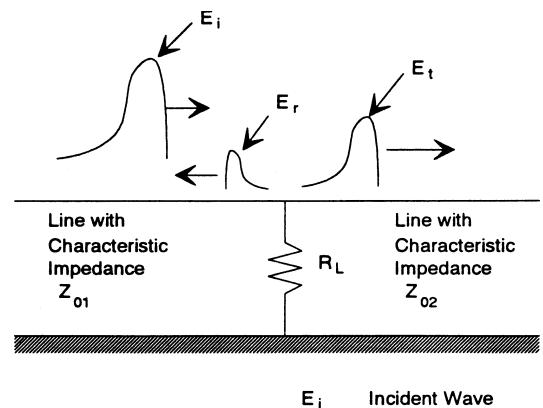


FIGURE 27-27 Transmission and reflection of waves at discontinuity.

If the discontinuity involves storage elements, that is, capacitors or inductors, the coefficients are not constant and the analysis becomes much more complex. The graphical method consists of monitoring all traveling waves on a line with the aid of a diagram, known as the *Bewley diagram*. The Bewley diagram provides, for every point in a system, all the waves present and the time at which they arrive. From this information, the actual voltage waveform at a specific point can be constructed as the superposition of all waves at that point. Such a construction is illustrated in Fig. 27-28.

Analytical Methods. Analytical methods are based on systematic algorithms for solution of the differential equations describing a system. A useful method is based on Laplace transforms. This

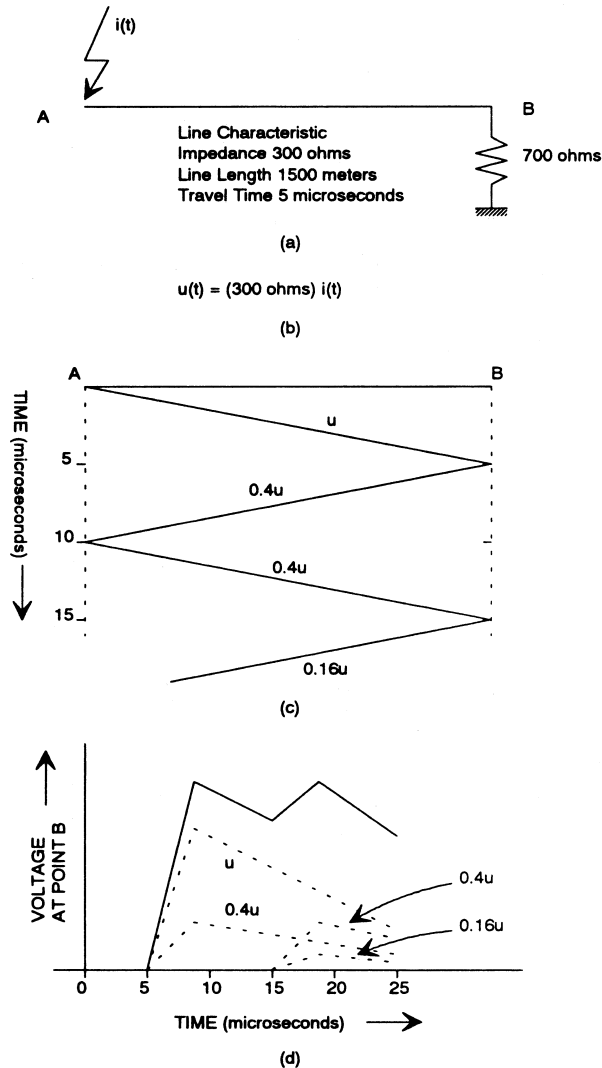


FIGURE 27-28 Illustration of the graphical method: (a) system description; (b) voltage surge due to lightning $i(t)$; (c) Bewley's diagram; (d) construction of voltage at point B as the superposition of all surges arriving at point B.

method transforms the differential equations describing a component into an equivalent circuit. An example follows. Consider the equation describing an inductor

$$v(t) = L \frac{di(t)}{dt}$$

Application of the Laplace transform on this equation yields

$$V(s) = sLI(s) - Li(0)$$

where $V(s)$ is the Laplace transform of $v(t)$ and $I(s)$ is the Laplace transform of $i(t)$.

The above equation represents the equivalent circuit of Fig. 27-29 (b3). This is known as the Thévenin form of the Laplace domain equivalent circuit. The process can be applied to any power system element described with a set of differential equations. Figure 27-29 illustrates the equivalent circuits in the Laplace domain of typical elements. Note that the equivalent circuits are represented with algebraic equations in complex variables.

Application of the analytical method involves transformation of the differential equations describing individual element with the Laplace transform into an equivalent circuit. Subsequently, nodal analysis (or loop analysis) is applied on the transformed elements to obtain the solution of the voltage at a point of interest as a function of the Laplace variable. Finally, application of the inverse Laplace transform will provide the time waveform of the voltage of interest. Many efficient algorithms were developed during 1975–1995 or so. The details can be found in the literature.

Numerical Methods. Numerical methods are based on transforming the differential equations describing a component into a discrete time equation. This transformation is achieved by proper integration of the differential equations. Many different integration methods can be applied. A very successful method is based on the trapezoidal integration method, because this method is an absolutely stable numerical method. The basic idea is explained as follows. Consider the differential equation

$$\frac{dx(t)}{dt} = ax(t)$$

Integration of this equation in the time interval $(t - h, t)$ yields

$$x(t) - x(t - h) = a \int_{t-h}^t x(\tau) d\tau$$

The integral on the right-hand side can be evaluated, assuming that the function $x(t)$ varies linearly in the time interval $(t - h, t)$, yielding

$$\int_{t-h}^t x(\tau) d\tau = \frac{h}{2} [x(t) + x(t - h)]$$

This integration is graphically illustrated in Fig. 27-30, which shows that the value of the integral is approximated with the area of the shown trapezoid—thus the name *trapezoidal integration*. Combining above equations and solving for $x(t)$

$$x(t) = \frac{(1 + ah/2)}{(1 - ah/2)} \cdot x(t - h)$$

If $x(0)$ is known, then the above equation can be applied to obtain the value $x(h)$, then $x(2h)$, $x(3h)$, etc. This is a simple algorithm useful for computing the solution at specified times, $h, 2h, 3h, \dots$

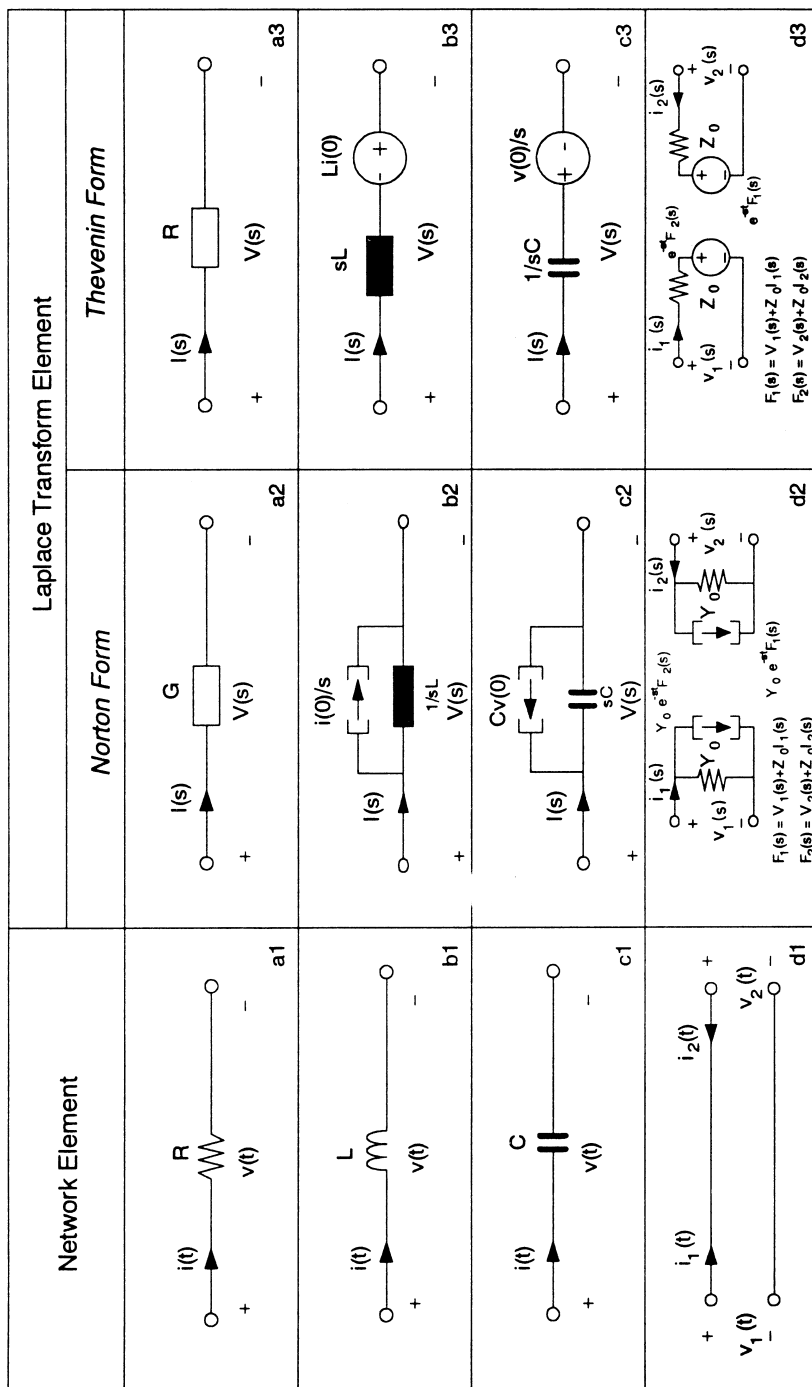


FIGURE 27-29 Equivalent-circuit representation in the Laplace domain. [From Meliopoulos (1988).]

The basic idea described above can be applied to the differential equations of any component. The result will be a set of algebraic equations which can be interpreted as a *resistive companion circuit*. The results for simple elements are illustrated in Fig. 27-31. Application of the method requires transformation of each element of the power system into a resistive companion circuit. The process replaces the actual system with a resistive network. This network includes voltage and current sources that depend on the state of the system at times less than t . Application of nodal analysis (or loop analysis) provides the solution for voltages and currents at time t . The process can start at time $t = 0$ and be repeated at times $t = h, t = 2h, \dots$, yielding the values of voltages and currents at times $t = 0, h, 2h, \dots$, etc. Further details can be found in Meliopoulos (1988).

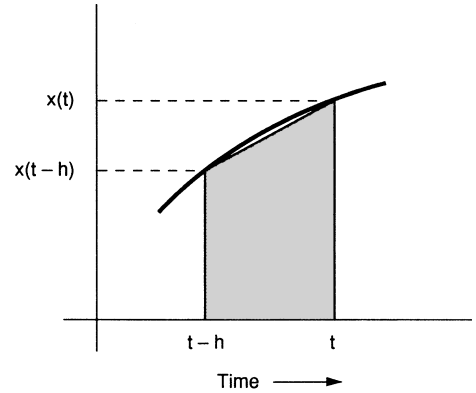


FIGURE 27-30 Graphical representation of the trapezoidal integration.

3-Phase Transmission Lines. 3-Phase transmission is represented with a distributed-parameter model. This model can be derived by considering an infinitesimal length of a 3-phase line as in Fig. 27-32b. Assuming an ideal line (zero losses and constant inductance and capacitance per unit length), the model equations are

$$CL \frac{\partial^2}{\partial t^2} v_{abc}(y, t) = \frac{\partial^2}{\partial y^2} v_{abc}(y, t)$$

$$CL \frac{\partial^2}{\partial t^2} i_{abc}(y, t) = \frac{\partial^2}{\partial y^2} i_{abc}(y, t)$$

$$L \frac{\partial}{\partial t} i_{abc}(y, t) = \frac{\partial}{\partial y} v_{abc}(y, t)$$

where

$$v_{abc}(y, t) = \begin{bmatrix} v_a(y, t) \\ v_b(y, t) \\ v_c(y, t) \end{bmatrix}$$

$$i_{abc}(y, t) = \begin{bmatrix} i_a(y, t) \\ i_b(y, t) \\ i_c(y, t) \end{bmatrix}$$

$$L = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ab} & L_{bb} & L_{bc} \\ L_{ac} & L_{bc} & L_{cc} \end{bmatrix}$$

is the inductance matrix per unit length of the line and

$$C = \begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ab} & C_{bb} & C_{bc} \\ C_{ac} & C_{bc} & C_{cc} \end{bmatrix}$$

is the capacitance matrix per unit length of the line, y is distance along line, and t is time.

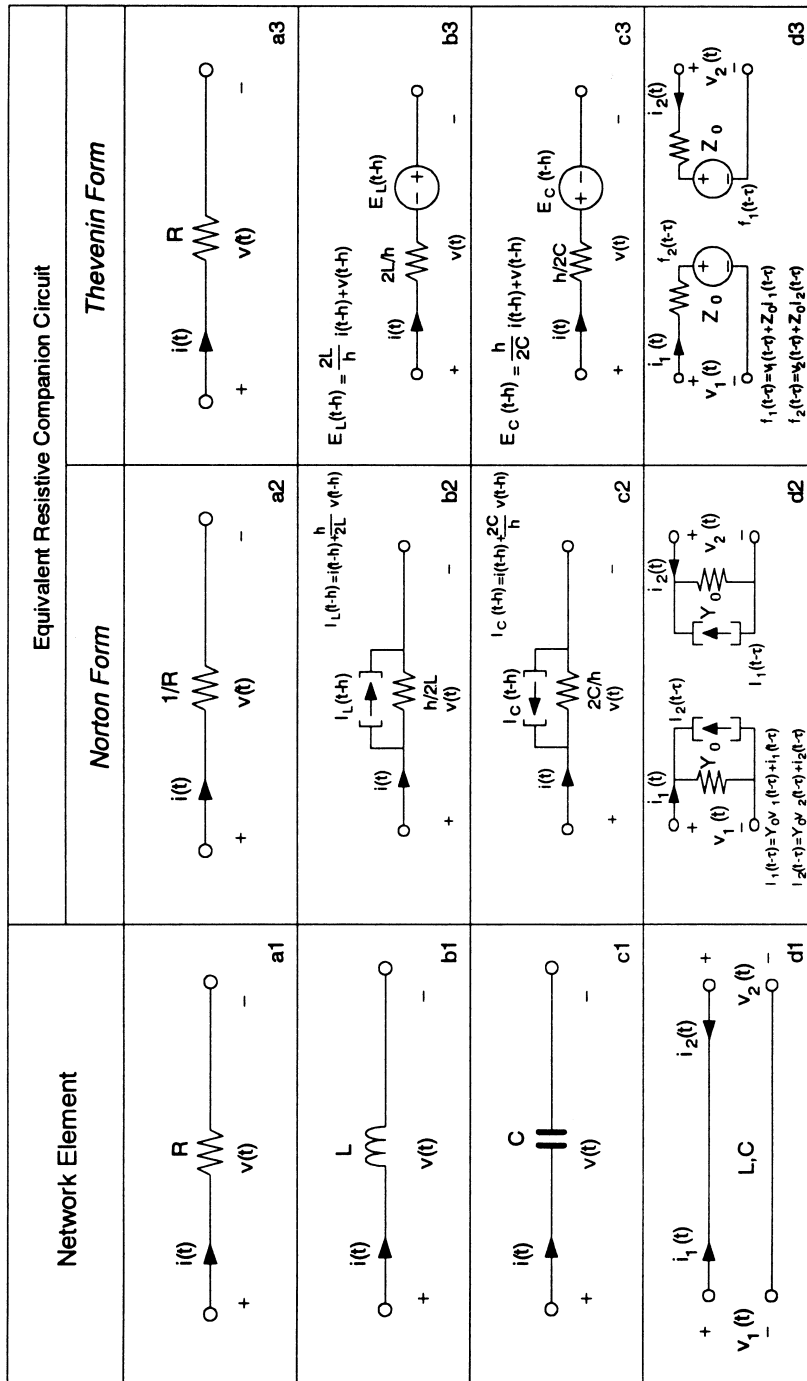


FIGURE 27-31 Equivalent resistive companion circuits. [From Melopoulos (1988).]

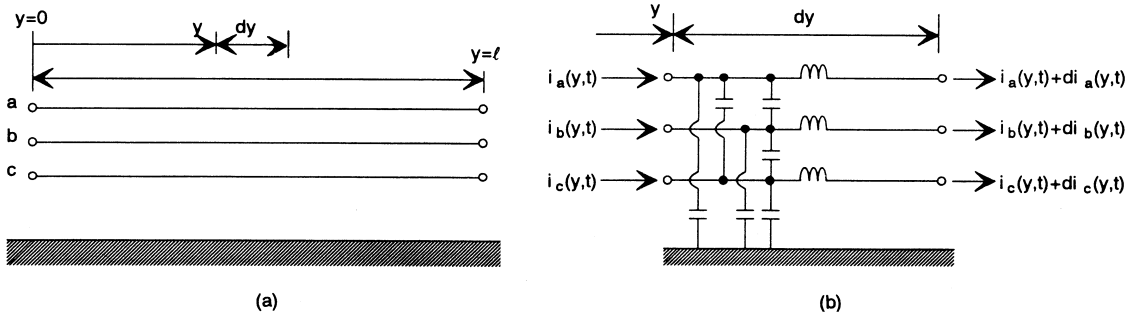


FIGURE 27-32 3-Phase line model: (a) 3-phase transmission line; (b) equivalent circuit of an infinitesimal length (dy) of 3-phase line.

This is a rather simplified model of a 3-phase line and yet very complex. To make clear the behavior of the 3-phase line, the concept of the *ideal continuously transposed line* will be introduced. This concept assumes a perfectly symmetrical line

$$L_{aa} = L_{bb} = L_{cc} = L_s$$

$$L_{ab} = L_{ac} = L_{bc} = L_m$$

$$C_{aa} = C_{bb} = C_{cc} = C_s$$

$$C_{ab} = C_{ac} = C_{bc} = C_m$$

Next, Karrenbauer's transformation is introduced as follows

$$v_{abc}(y, t) = K v_{gl}(y, t)$$

$$i_{abc}(y, t) = K i_{gl}(y, t)$$

where

$$v_{gl}(y, t) = \begin{bmatrix} v_g(y, t) \\ v_{l1}(y, t) \\ v_{l2}(y, t) \end{bmatrix}$$

$$i_{gl}(y, t) = \begin{bmatrix} i_g(y, t) \\ i_{l1}(y, t) \\ i_{l2}(y, t) \end{bmatrix}$$

and

$$K = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$$

Replacement of the actual voltages and currents $v_{abc}(y, t)$ and $i_{abc}(y, t)$ with the voltages and currents $v_{gl}(y, t)$ and $i_{gl}(y, t)$ through Karrenbauer's transformation yields the following transformed equations for the 3-phase line (Meliopoulos 1988)

Set 1 (ground-mode equations)

$$(L_s + 2L_m)(C_s + 2C_m)\frac{\partial^2}{\partial t^2}v_g(y, t) = \frac{\partial^2}{\partial y^2}v_g(y, t)$$

$$(L_s + 2L_m)(C_s + 2C_m)\frac{\partial^2}{\partial t^2}i_g(y, t) = \frac{\partial^2}{\partial y^2}i_g(y, t)$$

$$(L_s + 2L_m)\frac{\partial}{\partial t}i_g(y, t) = \frac{\partial}{\partial y}v_g(y, t)$$

Set 2 (line-mode 1 equations)

$$(L_s - L_m)(C_s - C_m)\frac{\partial^2}{\partial t^2}v_{l1}(y, t) = \frac{\partial^2}{\partial y^2}v_{l1}(y, t)$$

$$(L_s - L_m)(C_s - C_m)\frac{\partial^2}{\partial t^2}i_{l1}(y, t) = \frac{\partial^2}{\partial y^2}i_{l1}(y, t)$$

$$(L_s - L_m)\frac{\partial}{\partial t}i_{l1}(y, t) = \frac{\partial}{\partial y}v_{l1}(y, t)$$

Set 3 (line-mode 2 equations)

$$(L_s - L_m)(C_s - C_m)\frac{\partial^2}{\partial t^2}v_{l2}(y, t) = \frac{\partial^2}{\partial y^2}v_{l2}(y, t)$$

$$(L_s - L_m)(C_s - C_m)\frac{\partial^2}{\partial t^2}i_{l2}(y, t) = \frac{\partial^2}{\partial y^2}i_{l2}(y, t)$$

$$(L_s - L_m)\frac{\partial}{\partial t}i_{l2}(y, t) = \frac{\partial}{\partial y}v_{l2}(y, t)$$

Note that the complex equations for the 3-phase line have been replaced with three sets of equations, each set representing an ideal single-phase line. The characteristic impedance and speed of propagation of surges for the three ideal single phase lines are

Ground mode

$$Z_g = \frac{1}{Y_g} = \sqrt{\frac{L_s + 2L_m}{C_s + 2C_m}}$$

$$c_g = \frac{1}{\sqrt{(L_s + 2L_m)(C_s + 2C_m)}}$$

Line mode (1 or 2)

$$Z_l = \frac{1}{Y_l} = \sqrt{\frac{(L_s - L_m)}{(C_s - C_m)}}$$

$$c_l = \frac{1}{\sqrt{(L_s - L_m)(C_s - C_m)}}$$

This model of the line is illustrated in Fig. 27-33. The three sets of equations or three ideal single-phase line models above are known as (1) the ground mode g , (2) line mode 1 l_1 , and (3) the line mode 2 l_2 . The names become obvious if one considers excitation of the 3-phase line with one mode.

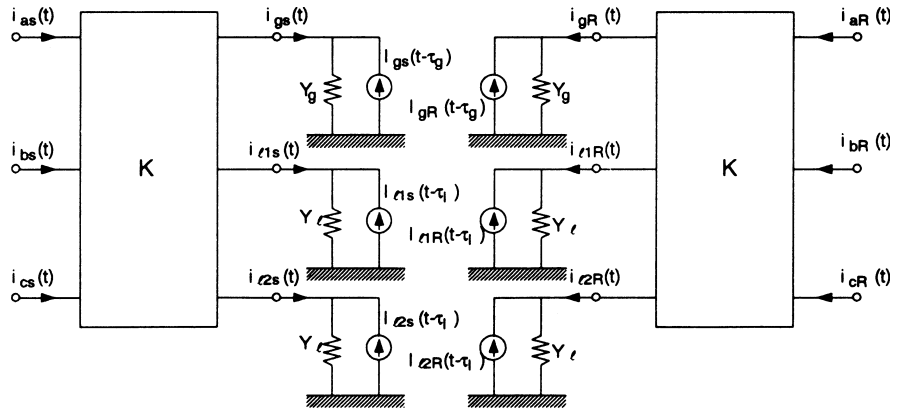


FIGURE 27-33 Equivalent circuit of a continuously transposed line.

For example, consider that the line is excited in such a way that $i_{l1}(y, t) = 0$ and $i_g(y, t) = 0$, $i_{l2}(y, t) = 0$. In this case, the actual phase currents will be

$$i_{abc}(y, t) = Ki_{gl}(y, t)$$

which yields

$$\begin{aligned} i_a(y, t) &= i_{l1}(y, t) \\ i_b(y, t) &= -2i_{l1}(y, t) \\ i_c(y, t) &= i_{l1}(y, t) \end{aligned}$$

This state of the line is illustrated in Fig. 27-34a. Note that there is a positive surge on phases a and c , which returns through phase b . All electric current surges are confined in the line conductors, thus the name line mode.

Consider now excitation with $i_g(y, t) \neq 0$, $i_{l1}(y, t) = 0$, and $i_{l2}(y, t) = 0$. In this case, the equation

$$i_{abc}(y, t) = Ki_{gl}(y, t)$$

yields

$$\begin{aligned} i_a(y, t) &= i_g(y, t) \\ i_b(y, t) &= i_g(y, t) \\ i_c(y, t) &= i_g(y, t) \end{aligned}$$

This state of the line is illustrated in Fig. 27-34b. Note that the surges on all phases are equal. The return current is through the earth, thus the name ground mode. The parameters of the various modes of propagation of surges in a 3-phase line are different. As an example, the following values apply to a 115-kV 3-phase line.

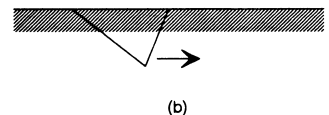
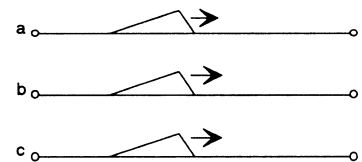
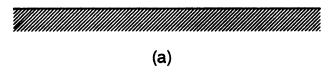
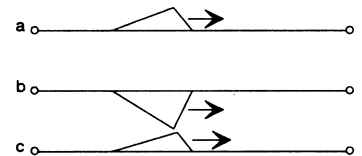


FIGURE 27-34 Modes of propagation along a 3-phase line: (a) line mode; (b) ground mode.

The inductance matrix is

$$L = \begin{bmatrix} 2.2289 & 1.032 & 0.8935 \\ 1.032 & 2.2289 & 1.032 \\ 0.8935 & 1.032 & 2.2289 \end{bmatrix} \mu\text{H/m}$$

Therefore $L_s = 2.2289 \mu\text{H/m}$ $L_m = 0.9858 \mu\text{H/m}$

The capacitance matrix is

$$C = \begin{bmatrix} 7.6737 & -1.9129 & -1.0065 \\ -1.9129 & 8.0184 & -1.9129 \\ -1.0065 & -1.9129 & 7.6737 \end{bmatrix} \times 10^{-12} \text{ F/m}$$

Therefore $C_s = 7.7886 \times 10^{-12} \text{ F/m}$ $C_m = -1.608 \times 10^{-12} \text{ F/m}$

Line mode (1 or 2):

$$Z_l = \sqrt{\frac{(L_s - L_m)}{(C_s - C_m)}} = 363.7 \Omega$$

$$c_l = \frac{1}{\sqrt{(L_s - L_m)(C_s - C_m)}} = 2.926 \times 10^8 \text{ m/s}$$

Ground mode:

$$Z_g = \sqrt{\frac{(L_s + 2L_m)}{(C_s + 2C_m)}} = 959.1 \Omega$$

$$c_g = \frac{1}{\sqrt{(L_s + 2L_m)(C_s + 2C_m)}} = 2.283 \times 10^8 \text{ m/s}$$

When lightning hits a 3-phase line, all modes of propagation are excited. The overvoltage of the 3-phase line as a result of the lightning stroke is determined from the parameters of all the modes. Later, examples of these calculations will be provided.

Frequency-Dependent Models. The parameters of power-system elements are frequency dependent. As an example, consider the ground-mode resistance of a 3-phase line. This resistance value may change *several orders of magnitude* in the frequency range 60 Hz (power frequency) to 1 MHz. This increase of resistance is mainly due to skin-effect-type phenomena. The higher resistance values at high frequencies tend to attenuate higher-frequency components of transient overvoltages with the end effect of reducing the maximum overvoltages. Computer models to account for the frequency dependence have been developed for almost all power components. The reader is referred to the literature. Frequency-dependent models are complex, but, on the other hand, they provide a better representation of the real system. As an example, consider Fig. 27-35. The figure illustrates comparison of measured and computed switching transients in a 224.15-mi-long 230-kV line. The single-line diagram of the system is illustrated in Fig. 27-36. The tests were performed by Bonneville Power Administration. The calculated switching transient was performed with a frequency-dependent model (Cokkinides and Meliopoulos 1988). Note that the maximum switching overvoltage is 1.81 pu. It is important to note that simulation of the same system assuming an ideal continuously transposed line results in a maximum switching overvoltage of 2.05 pu. The conclusion is that frequency-dependent models are more realistic.

Grounding Models. Grounding plays an important role in dissipation of lightning strokes and therefore controlling overvoltages resulting from lightning. Yet, grounding has been widely misunderstood and proper analysis models are scarce. Modeling of grounding systems is a rather complex task, and it is strongly coupled to the overall modeling procedure for power systems. Two distinct approaches apply: (1) grounding models for low frequency generally consider grounds as a pure resistance and thus dc analysis models are utilized, based on the method of moments or relaxation methods; (2) grounding models for higher frequencies require complete electromagnetic analysis. For this purpose, finite element analysis or the method of moments can be utilized. Since the grounds are typically complex systems, simplifications are typically introduced. A rule of thumb for selecting dc models or the more complex models is to compare the largest dimension of a grounding system l to the depth of penetration $\delta = \sqrt{2l/\mu\omega\sigma}$. If $l > 0.1\delta$, then a complete model is necessary. In this expression, μ is the permeability of the medium, ω is the frequency in radians per second, and σ is the conductivity.

The choice of the grounding model can be crucial. As an example, consider a grounding system consisting of a counterpoise buried in soil of $100 \Omega \cdot \text{m}$. The dc ground resistance of this system is 2.29Ω . The frequency-dependent impedance is much higher for high frequencies and approaches 2.29Ω for frequencies below 50 kHz. As a result, a lightning discharge through this ground will require a frequency-dependent ground model to accurately predict the transient overvoltages. As an example, Fig. 27-37 shows the differences between the correct model and the dc model for the standard lightning waveform. The example emphasizes the importance of selecting the proper model for the grounding system.

Grounding systems play an important role in propagation of surges from high-voltage power systems to lower-voltage secondary systems. Specifically, transients initiated in the power system can travel through the grounding system and enter the secondary power system of a facility, reaching sensitive electronic equipment. Transformers do not exist in the path of a neutral. Thus, high-frequency transients travel almost unattenuated through the neutral. Attenuation is provided only by the grounds if the neutral is multiply grounded. A proper model of the grounds, neutrals, and the power system can provide a good tool to determine the transient overvoltages reaching a specific piece of equipment. As an example, consider a facility served by a 1-mi (1.6 km) underground distribution cable as in Fig. 27-38. The underground cable is fed from an overhead distribution circuit, which is subject to lightning. At such a service entrance, transients can enter a facility through the cable concentric neutral and the ground conductors.

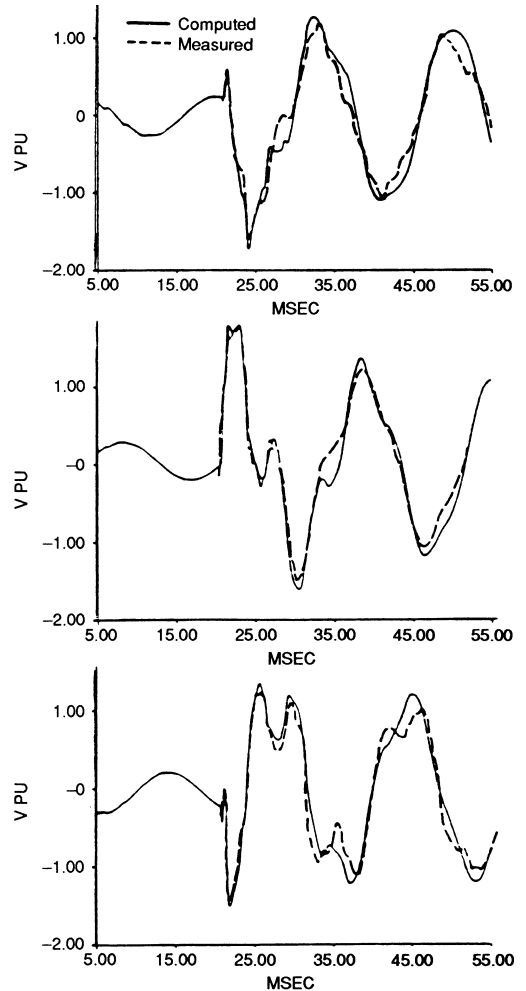


FIGURE 27-35 Comparison of simulation and test results of switching surges: (a) phase A transient voltage; (b) phase B transient voltage; (c) phase C transient voltage. [From Cokkinides and Meliopoulos (1988).]

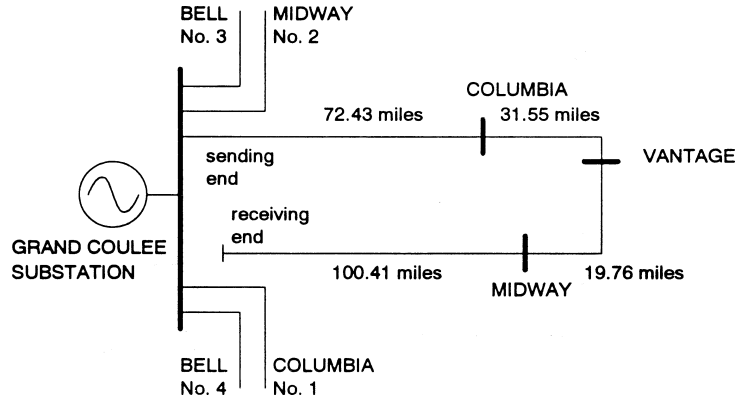


FIGURE 27-36 Illustration of system for switching surge test. (Bonneville Power Administration.)

Probabilistic Methods. The objective of these methods is to provide a probabilistic description of overvoltages in a specific power apparatus. The method takes into consideration the uncertainty in parameters affecting the overvoltages. Some of the uncertain parameters are listed in Table 27-5.

The probabilistic methods consist of the following three components:

1. A probabilistic model for the uncertain parameters
2. An analysis model for the system under study
3. A Monte Carlo simulation method

The result of the method is the probability distribution of the overvoltages at the apparatus of interest. Given the probabilistic model for the uncertain parameters and an analysis model for the system under study, the Monte Carlo simulation consists of the following steps:

Step 0: Set count of trial n equal to 0.

Step 1: Generate (randomly) a sample of parameters from the probabilistic model of uncertain parameters (crest value of lightning stroke, rise time, fall time, location of incidence, etc.).

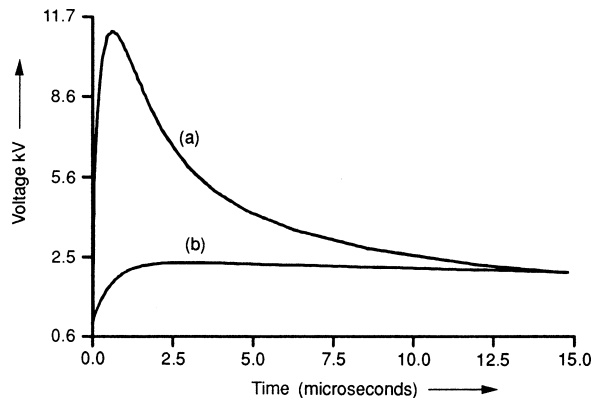


FIGURE 27-37 Transient voltage on a 300-ft counterpoise from a 1.2-50-m/s lightning wave of a 1-kA crest: (a) frequency-dependent model; (b) frequency-independent model.

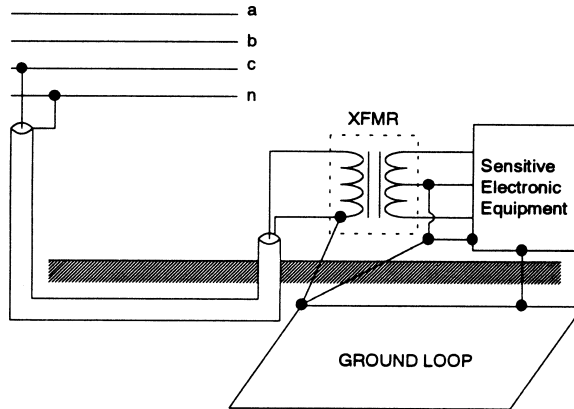


FIGURE 27-38 Illustration of a typical service entrance to a commercial or industrial facility.

Step 2: Use the analysis model and the parameter values determined in step 1 to evaluate the maximum overvoltage at points of interest (or other quantities of interest). Store the computed values.

Step 3: Repeat steps 1, 2, and 3 until the number of trials = n . Then go to step 4.

Step 4: Use the stored computed values of overvoltages (or other quantities of interest) to generate histograms and/or probability distribution functions.

TABLE 27-5 Typical Parameters with Uncertainty

Lightning	Crest value
	Rise time
	Frequency of occurrence
	Shielding failure
	Other
Switching	Switch closing time
	Time of preinsertion of resistors
	Trapped charge
	Other

The utility of probabilistic methods is quite obvious. They provide the tool to determine not only the expected overvoltages but also the frequency of occurrence. For external insulation protection practices, probabilistic methods provide an indispensable tool for optimal designs.

27.6 OVERVOLTAGE PROTECTION DEVICES

With certainty, temporary overvoltages on power-system apparatus will exceed their withstand capability. In this case, if the apparatus is left unprotected, insulation failure will occur. Therefore, it is necessary to protect power system components against overvoltages. The philosophy and objectives of this protection vary depending on the type of overvoltages, frequency, effects of insulation failure, and cost of repair. These issues will be discussed later. In this section, we will be concerned with available protection devices, their characteristics, and protection levels. An overvoltage protection device should ideally limit the voltages across the insulation of a power apparatus below a specified value. This specified value is called the *protection level*. The ideal protection device has the voltage-current characteristic indicated in Fig. 27-39. Specifically, if the voltage across the protection device is less than the protection level, then the protection device should have an infinitely large impedance. If the voltage across the protection device is higher than the protection level, then the protection device should allow the flow of electric current through it

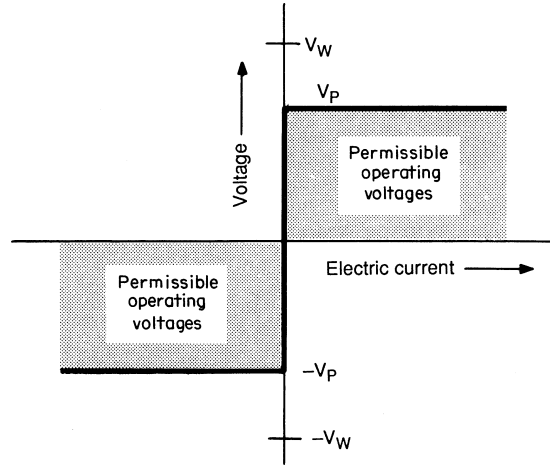


FIGURE 27-39 Voltage-current characteristics of the ideal over-voltage protection device.

in such a way that the voltage is clipped to the protection level value. Such a characteristic can be mathematically described with the equation

$$i(t) = i_0 \left\{ \frac{\text{abs}[v(t)]}{v_p} \right\}^n \text{sign}[v(t)] \quad (27-1)$$

where i_0 = a constant
 v_p = protection level
 $\text{abs}(\cdot)$ = absolute value of the argument ($\cdot$)
 $v(t)$ = voltage across the protective device
 $\text{sign}[v(t)]$ = sign of voltage $v(t)$, + or -
 n = a very large number

The protection characteristics of Fig. 27-39 correspond to a very large value of n .

Of course, a protection device with these characteristics does not exist. Research and development has resulted in protection devices which come close to that of Fig. 27-39 to varying degrees. It is important to note that the research and development of protection devices has been evolutionary; over the years the following major breakthroughs have occurred:

- Air gaps
- Gapped surge arresters
- Expulsion arresters
- Gapped valve-type arresters
- Gapped silicon carbide (SiC)
- Metal oxide varistors
- Shunt-gapped metal oxide varistors (MOVs)

The most important application characteristics of a protection device are the protection level and the reseal level. These are defined as follows:

- Protection level:* The maximum voltage, which will be allowed by the device across its terminals.
- Reseal level:* The maximum voltage below which the protection device will disallow significant electric current through it.

For best results, it is expedient that these two parameters be as close as possible. Observe that for the ideal protection device, the protection level is equal to the reseal level. In order to quantify the protection quality of various technologies of protective devices, the following definition is introduced:

Protection quality index (PQI). The protection-quality index is defined as the ratio of the reseal level over the protection level:

$$PQI = \frac{V_r}{V_p}$$

Note that the ideal protective device has a protection-quality index of 1. As should be expected, the protective capabilities of protective devices increase with every breakthrough in the technology. Air gaps provide rudimentary protection, gapped SiC surge arresters provide improved protection, and finally MOVs provide even better protection. Within each class of technology, many variations exist. The next paragraphs will discuss the above technologies.

Air (Spark) Gaps. A spark gap was the first protection device to be applied on a power system. It can be constructed with two electrodes placed at a certain distance. The shape of the electrodes varies depending on the application—for example, two wires, a wire and a planar electrode, or two spheres. When the voltage across the air gap exceeds a certain value, an arc will initiate between the electrodes. The voltage across the arc will depend on the current of the arc, the length of the arc, and time. A typical variation of the voltage across the gap is illustrated in Fig. 27-40. The protection level as well as the reseal level, indicated as maximum permissible operating voltage across the gap, are shown. Note that for good protection, the protection quality index (the ratio V_r/V_p) should be maximized. Unfortunately, air gaps exhibit very low protection quality index. In many applications, and in order to improve the protection quality index, the electrodes are shaped in such a way as to force the arc to elongate and therefore increase the voltage reseal value V_r .

Gapped Surge Arresters. Gapped surge arresters consist of a series of spark gaps with or without series blocks of nonlinear resistors, which act as current limiters. The construction of such an arrester is illustrated in Fig. 27-41.

The function of the air gap is to isolate the current limiting block of the surge arrester from the power frequency voltage under normal operating conditions. The air gap is necessary because the current limiting block will fail thermally if subjected to the continuous normal power frequency

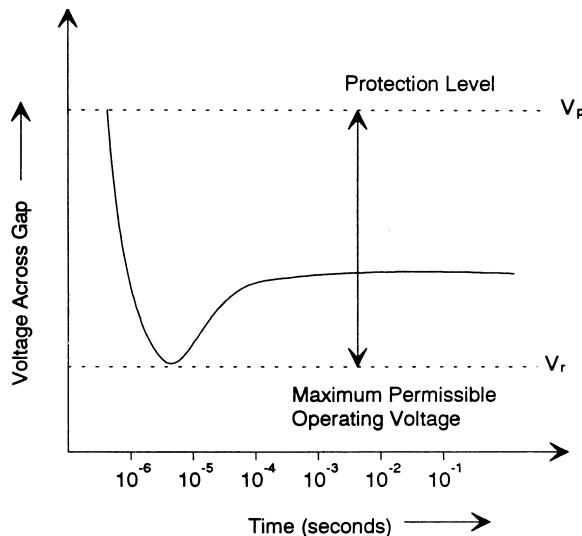


FIGURE 27-40 Typical voltage-time characteristic of a long air gap.

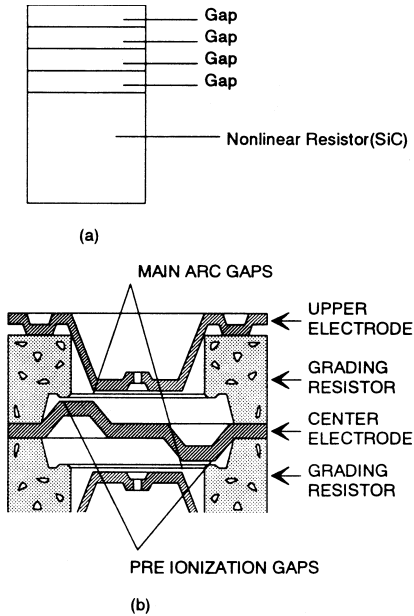


FIGURE 27-41 Construction of a gapped arrester: (a) block diagram; (b) detail of a gap.

The current-limiting block in modern gapped arresters is constructed from SiC. The block has non-linear resistance characteristics that are controlled with the manufacturing process. Specifically, the block is constructed from SiC crystals which are ground into powder form and then are mixed and pressed together with insulating material, forming a block. In this way, an SiC particle partially touches other particles and partially is insulated by the insulating material. The nonlinear properties

voltage. Elaborate designs of air gaps have been developed, which assure (1) consistent sparkover voltage and (2) arc extinction (resealing) after the overvoltage ceases to exist.

Consistent sparkover voltage is achieved by either a trigger gap or a preionizer. In order to prevent damage of the trigger mechanism, the main current is not allowed to pass through it by use of grading resistors as is illustrated in Fig. 27-41, but through the main arc gaps. To ensure arc extinction and good resealing properties, a mechanism is provided for the control of the arc. Specifically, the main current is passed through a coil. The magnetic field of the coil is established in the space of the arc and is oriented so as to force the arc into a serrated-tooth chamber. The end result of this interaction is that the arc is elongated, cooled, and the voltage across the arc becomes substantial. Figure 27-42 illustrates the buildup of the voltage across the arc due to this mechanism. An illustration of the serrated-tooth chamber is illustrated in Fig. 27-43. The elongated arc improves the capability of the arrester to reseal when the current through it decreases after the overvoltage ceases to exist. It is important to note that the arc control process takes a relatively long time (hundreds of microseconds) to develop full voltage across the gap. This means that for fast transients, that is lightning, almost the entire voltage appears across the current-limiting block.

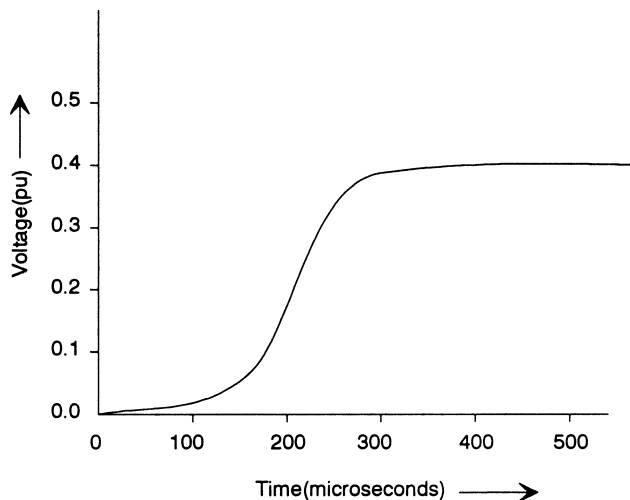


FIGURE 27-42 Evolution of voltage across the arc of a gapped arrester.

are due to the resistance-temperature properties of the junction between the SiC crystals. This relationship is illustrated in Fig. 27-44.

The combined operation of the gap and the current-limiting block result in the voltage-current characteristic illustrated in Fig. 27-45. It is important to note that, while the sparkover voltage V_s is typically consistent, the voltage-current curve depends on the waveform of the electric current, since the gap voltage is time dependent.

Gapped SiC arresters are subject to power-follow current because of the poor nonlinear characteristics of the SiC block. Specifically, after sparkover and after the temporary overvoltage has subsided, if the power voltage across the arrester is substantial, a relatively high current will continue to flow through the arrester. The reason can be easily visualized if one considers that the arc in the gap is a low-resistance conductor and that the current is primarily determined by the voltage-current characteristics of the SiC block. The situation is illustrated in Fig. 27-46. In the figure, the power-follow current of a SiC gap arrester is also compared to the power-follow current of an MOV arrester, which is discussed next.

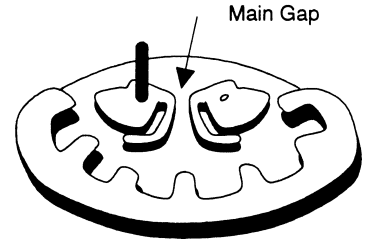


FIGURE 27-43 Illustration of a serrated-tooth chamber of a gapped arrester.

Metal Oxide Varistor Arresters. An MOV is formed from a variety of materials via a manufacturing process, which provides the desired electrical properties to the varistor. These electrical properties are not existent in the raw materials. In other words, the electrical properties of the final product are completely dependent on the manufacturing process. Much research effort has been expended to achieve electrical properties of the varistor close to those of the ideal protective device. The typical structure of a metal oxide varistor consists of highly conductive tiny particles of metal oxide (usually zinc oxide, ZnO) suspended in a semiconducting material. This structure is illustrated in Fig. 27-47. The manufacturing process determines the size of the metal oxide particles as well as the thickness and resistivity of the semiconducting material. The key to a good manufacturing process is that the conductive metal oxide particles do not touch each other but are separated by semiconducting material. This structure gives the varistor the properties of a pair of back-to-back-connected zener diodes. A typical voltage-current characteristic of an MOV is illustrated in Fig. 27-46. It should be understood that this function holds for negative voltages and currents.

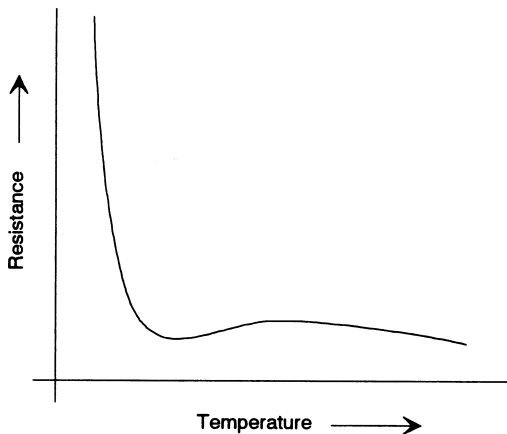


FIGURE 27-44 Typical resistance versus temperature of junction between SiC crystals.

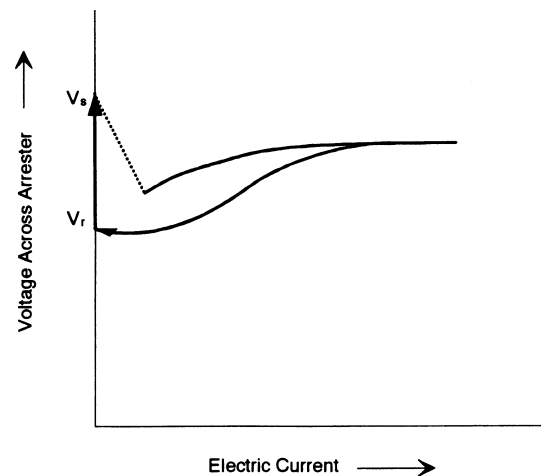


FIGURE 27-45 Typical voltage-current characteristics of a modern SiC gapped arrester.

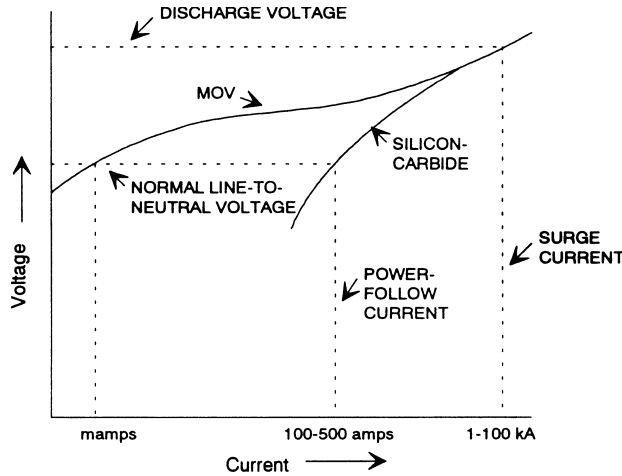


FIGURE 27-46 Illustration of power-follow current for a SiC gapped arrester and an MOV arrester.

In addition to this characteristic, it is necessary that the MOV material be capable of absorbing energy losses during conduction. The average energy absorption capability of a conventional ZnO varistor is about 150 to 200 J/cm³. Recent advances in MOV technology under Electric Power Research Institute sponsorship resulted in new formulations and manufacturing processes for MOVs. The new MOVs are capable of absorbing 4 to 5 times more energy per volume as above.

The first designs of MOV arresters were subject to problems. The most common were thermal runaway and failures due to moisture ingress causing insulation failures. Thermal runaway can occur because an MOV is typically applied to the energized conductor without a series gap, and a small electric current always flows through the MOV during normal operating conditions. This small current and the associated ohmic losses can potentially raise the temperature of the MOV to the point that its electrical properties deteriorate, allowing more current to flow and further raising the temperature until failure. However, improvements in metal oxide materials and in packaging resulted in robust MOV arresters. The present state of the art and the superior properties of the MOV arresters make them the protection device of choice.

The first commercially available MOV arresters were gapless. As a result, the MOV block is continuously subjected to the power frequency voltage. The performance of the MOV block under this condition is very important for determining the life of the arrester. A deep understanding of these characteristics is essential for the proper application of MOV arresters.

First, observe that the voltage-current characteristic for an MOV arrester in Fig. 27-46 exhibits a knee for small currents (in the milliamperage region). The knee is defined to be near the voltage required across the MOV block to cause 1 mA/cm² of current to flow through the block. It is important to mention that while the voltage-current characteristic of an MOV block in the protection region (high current flow) is insensitive to the temperature of the block, the voltage-current characteristic near the knee is temperature-sensitive. This is illustrated in Fig. 27-48.

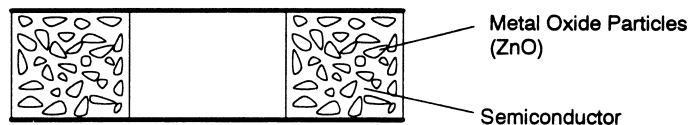


FIGURE 27-47 Structure of a metal oxide varistor (MOV). Size is exaggerated for illustration purposes.

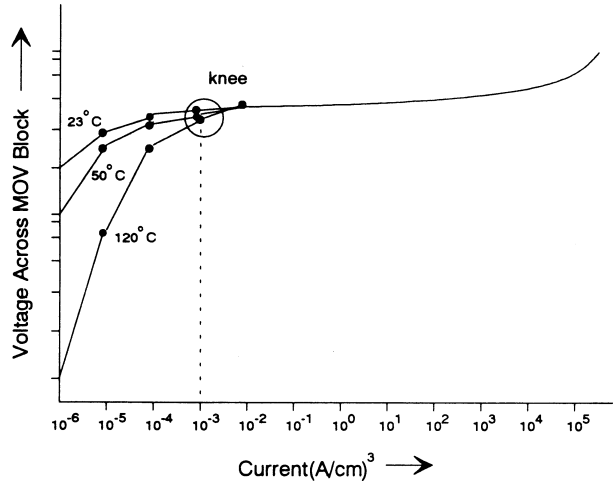


FIGURE 27-48 Voltage-current characteristic is temperature-sensitive near the knee of the curve.

Figure 27-49 illustrates the voltage versus current curves for an MOV arrester for different levels of applied voltage (sinusoidal, 60 Hz) expressed in pu of arrester rating. Note that for an applied voltage near nominal (1.05 pu), the electric current through the arrester is mostly capacitive (voltage and current are approximately 90° apart) and of low value on the order of a milliampere. As the voltage increases, the electric current increases much faster. It can be observed from the figure that the increase of the current occurs in the component, which is in phase with the voltage (resistive current) while the capacitive component remains constant.

The current flow through the arrester is responsible for power loss within the MOV block, which increases the temperature of the block. A typical power loss—applied voltage function is illustrated in Fig. 27-50. Note that as the voltage increases the power loss increases disproportionately. Increased losses and increased operating temperature have a detrimental effect on the MOV arrester life. Figure 27-51 illustrates the expected MOV arrester life as a function of continuously applied sinusoidal voltage.

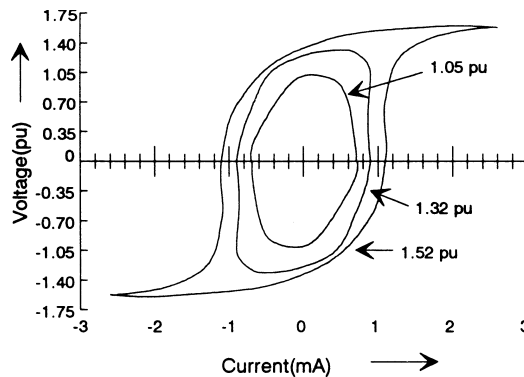


FIGURE 27-49 Illustration of voltage vs. current through an MOV for different levels of a sinusoidal (60-Hz) applied voltage.

27-44 SECTION TWENTY-SEVEN

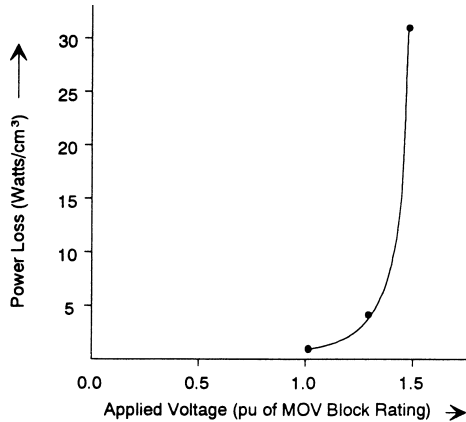


FIGURE 27-50 Typical power loss of an MOV block vs. applied voltage.

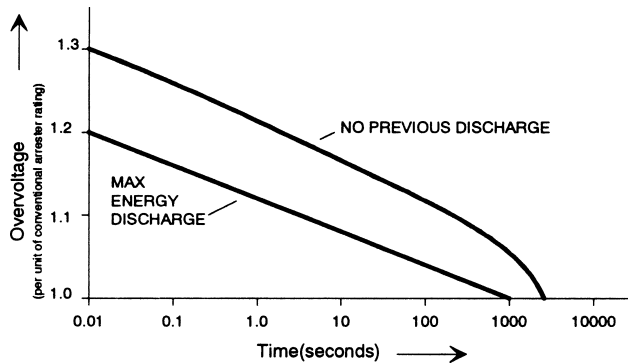


FIGURE 27-51 Expected MOV arrester life as a function of continuously applied power frequency voltage.

An MOV block, because of its dimensions, exhibits a capacitance and an inductance. Both of them are insignificant at low frequencies. However, at higher frequencies they affect the performance of the arrester. This performance is illustrated in Fig. 27-52, which shows the discharge voltage across the MOV arrester as a function of time for specific values of electric current through the arrester. From this figure it is obvious that the protective level of an MOV arrester will depend on the waveform of the overvoltage.

This behavior of the MOV surge arrester can be captured with the model of Fig. 27-53. Note that this model consists of two parallel resistance-inductance (R - L) circuits, a parasitic capacitance, and two nonlinear resistors. The nonlinear resistor RN_0 , represents the nonlinear characteristics of the arrester to fast front end surges, while the nonlinear resistor RN_1 represents the nonlinear

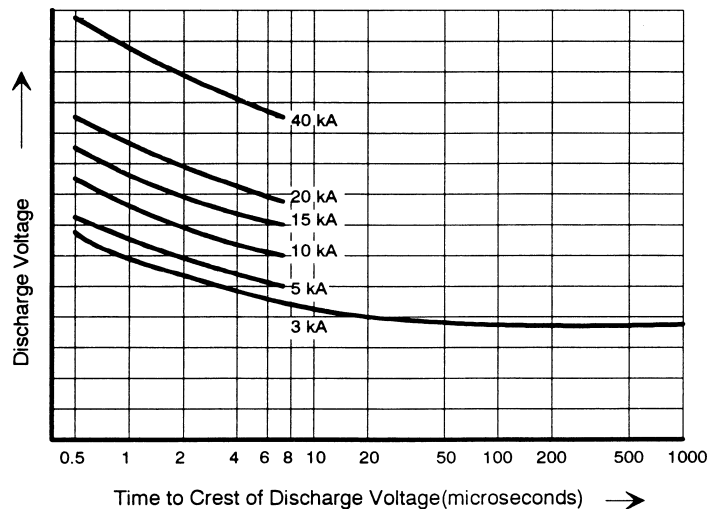


FIGURE 27-52 Discharge voltage across an MOV arrester vs. time for various current levels through the arrester.

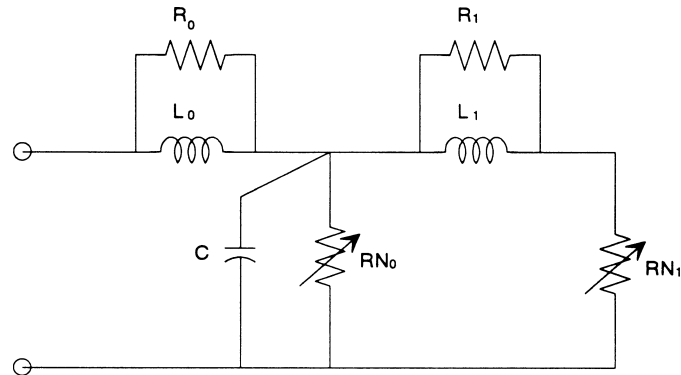


FIGURE 27-53 Nonlinear MOV arrester model.

characteristics of the arrester to slow front-end surges. The parameters of the model are selected to match the measured discharge characteristics of the arrester. Typical parameters are illustrated in Fig. 27-54.

It can be observed in Fig. 27-48 that, as the arrester discharge current increases in an MOV, the desirable nonlinear characteristics are deteriorating. This occurs in Fig. 27-48 at discharge currents above 10 kA. Specifically, the discharge voltage at currents above 10 kA increases, resulting in inferior protection characteristics. In this aspect SiC arresters are superior to MOVs because SiC arresters do not exhibit this abrupt increase of discharge voltage at higher currents. The performance of MOVs at higher discharge currents can be improved by equipping them with a shunt gap (Westrom 1990). Such a construction is illustrated in Fig. 27-55. Specifically, an MOV block in an arrester is equipped with a shunt spark gap. The gap is designed to spark over whenever the discharge current through the arrester exceeds a certain value, for example 10 kA. In this way, when the

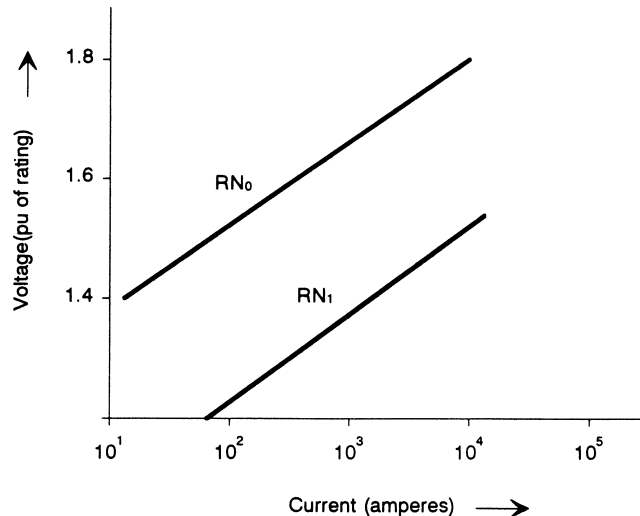


FIGURE 27-54 Typical nonlinear voltage-current characteristic of the nonlinear resistor RN_0 and RN_1 .

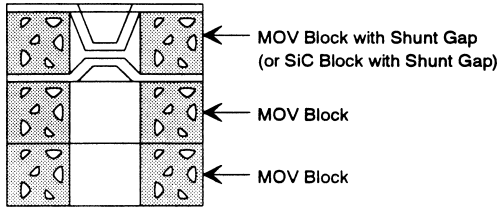


FIGURE 27-55 Typical construction of a shunt-gap MOV arrester.

discharge current increases beyond the value at which the desirable nonlinear characteristics of the MOV block start to deteriorate, the shunt gap sparks over, resulting in reduced discharge voltage and therefore improved protection characteristics.

Protective Margins. Another important concept is the protection margin (PM). The protective margin is related to the properties of the protective device relative to the with-

stand capability of the power apparatus under protection. For the ideal situation depicted in Fig. 27-39, the protection margin is defined as

$$PM = \frac{V_w - V_p}{V_p}$$

where V_w is the withstand capability of the power apparatus under protection and V_p is the protection level.

Because both the protection level of a surge arrester and the withstand capability of a power apparatus depend on the rise time of the transient overvoltage, it is expedient to define protective margins for the standard surge waveforms. In this sense, the following protective margins are defined.

1. Equivalent front-of-wave protective margin (PM_{fow})

$$PM_{fow} = \frac{V_{cww} - V_{p,fow}}{V_{p,fow}} \times 100$$

where V_{cww} is the equipment chopped-wave withstand (cww) voltage and $V_{p,fow}$ is the arrester protection level for the front of wave (fow).

2. Equipment impulse protection margin (PM_i)

$$PM_i = \frac{BIL - V_{p,d}}{BIL} \times 100$$

where BIL is the equipment basic insulation level and $V_{p,d}$ is the arrester protection level for a full impulse wave.

3. Equipment switching protective margin (PM_s)

$$PM_s = \frac{BSL - V_{p,ss}}{V_{p,ss}} \times 100$$

where BSL is the equipment basic switching insulation level and $V_{p,ss}$ is the arrester protective level for a switching surge.

The definition of these three protective margins is illustrated in Fig. 27-56. In this definition one should bear in mind that the arrester protective levels may be defined differently for gapped and gapless arresters. Specifically, the definition of the protective levels for gapped and gapless arresters follows.

- $V_{p,fow}$, arrester protection level for front of wave

Series-gapped arresters—front-of-wave sparkover: standard test dictates the rate of rise of front of wave to be 5.89 pu V/ μ s

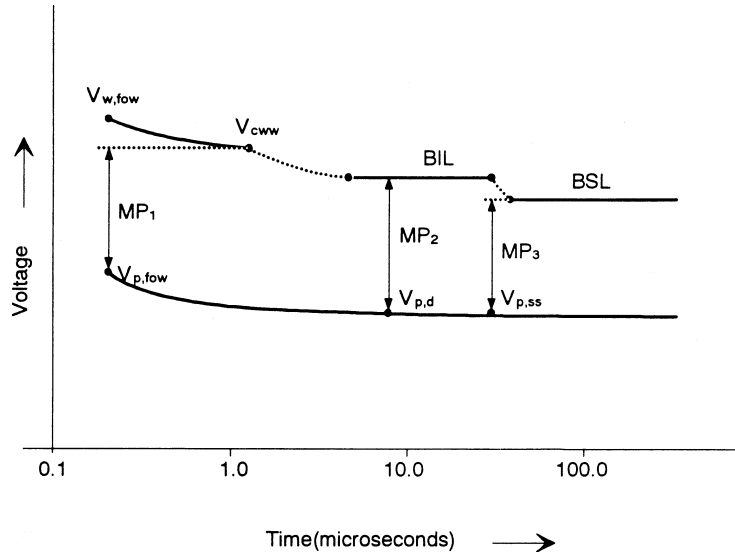


FIGURE 27-56 Illustration of the protection margin definition.

Gapless MOV arresters—front-of-wave sparkover: the highest discharge voltage to a surge-current impulse with $0.5 \mu\text{s}$ rise time and of specified crest (typically 3 to 40 kA)

Shunt-gapped MOV arresters—front-of-wave sparkover: same as for gapless MOV arresters

- $V_{p,d}$, arrester protection level for a full impulse wave

Series-gapped arresters—let-through level: the highest full impulse expected to cause sparkover after $8 \mu\text{s}$

Gapless MOV arresters—discharge voltage: the highest discharge voltage to a surge-current impulse ($8 \times 20 \mu\text{s}$) of specified crest (typically 5 to 20 kA)

Shunt-gapped MOV arresters—discharge voltage: same as for gapless MOV arresters

- $V_{p,ss}$, arrester protection level for a switching impulse

Series-gapped arresters—switching surge sparkover: the highest full impulse causing sparkover at a time greater than $30 \mu\text{s}$

Gapless MOV arresters—switching surge discharge voltage: the highest discharge voltage to a current switching impulse of specified crest (typically 3 kA)

Gapped MOV arresters—switching surge discharge voltage: same as for gapless MOV arresters

Arrester Classification. Arresters can be classified into the following groups:

Station arresters

Intermediate arresters

Distribution arresters

Secondary, industrial, and commercial arresters

This classification is based on kilovolt ratings. Historically, station arresters provide the lowest protective levels relative to their rating (i.e., they have the highest protection quality index) and are capable of discharging the highest amount of energy. Intermediate arresters have somewhat higher protective levels relative to their rating and are capable of discharging somewhat less energy. Distribution and secondary, industrial, and commercial arresters have even higher protective levels and are capable of discharging even less energy. This historical classification and description of arresters may not be valid

anymore. For example, there are MOV products that use MOV blocks for secondary arresters of the same quality as station class arresters, and therefore exhibit a very high protection quality index. It is important, however, to adopt this classification for consistency with standards.

Specific voltage ratings, protective levels, and other mechanical characteristics of complete arrester units can be found in the ANSI/IEEE standards. As an example, Table 27-6a, taken from ANSI/IEEE C62.1-1989, lists the standard voltage ratings for surge arresters. Table 27.6b lists the

TABLE 27-6a Surge Arrester Voltage Ratings in Kilovolts

Secondary arresters	Distribution arresters	Intermediate arresters	Station arresters
0.175			
0.650			
	1		
	3	3	3
	6	6	6
	9	9	9
	10		
	12	12	12
	15	15	15
	18		
	21	21	21
		24	24
	25		
	27		
	30	30	30
		36	36
		39	39
		48	48
		60	60
		72	72
		90	90
		96	96
		108	108
		120	120
			144
			168
			180
			192
			240
			258
			276
			294
			312
			372
			396
			420
			444
			468
			492
			540
			576
			612
			648
			684

TABLE 27-6b MOV Arrester Ratings in Kilovolts*

Duty-cycle voltage (kV rms)	MCOV (kV rms)	Duty-cycle voltage (kV rms)	MCOV (kV rms)
3	2.55	144	115
6	5.1	168	131
9	7.65	172	140
10	8.4	180	144
12	10.2	192	152
15	12.7	228	180
18	15.3	240	190
21	17	258	209
24	19.5	264	212
27	22	276	220
30	24.4	288	230
36	29	294	235
39	31.5	312	245
45	36.5	396	318
48	39	420	335
54	42	444	353
60	48	468	372
72	57	492	392
90	70	540	428
96	76	564	448
108	84	576	462
120	98	588	470
132	106	612	485

*For ratings not shown, consult with the manufacturer.

MOV arrester ratings taken from ANSI/IEEE std. C62.11-1999. Another example is Table 27-7, taken from ANSI/IEEE C62.2, which provides several important arrester parameters and application data for station- and intermediate-class arresters. More accurate data for specific products are available from the manufacturers.

There are a variety of commercial transient voltage suppression devices based on MOV technology. The quality of some of these products in terms of (1) their nonlinear characteristics, (2) energy absorption characteristics, and (3) current handling capability is very high. As an example, Table 27-8 illustrates the characteristics of a 480-V rated transient voltage suppression device, HA series. Figure 27-57 also illustrates the voltage-current characteristic of this device. By a simple fitting procedure, the nonlinear characteristic of this device in the range 1 to 1000 A is approximately described by Eq. (27-1), where $n \approx 24$. This is a relatively high exponent, suggesting a rather high protection quality index.

27.7 OVERVOLTAGE PROTECTION (INSULATION) COORDINATION

The objective of overvoltage protection coordination, otherwise known as insulation coordination, is to minimize the number of insulation failures and therefore the number of interruptions. This has been a fundamental task of power engineering with a profound effect on the reliability of the system. Insulation coordination methods have evolved from the ad hoc procedures of the past to the highly sophisticated computer methods of today. Yet protection schemes remain an art, and a review of the evolution of methods provides an invaluable insight. By necessity, the methods are based on incomplete data or parameters with substantial uncertainty. As a result, present models are incomplete and interpretation of results is necessary.

TABLE 27-7 Station and Intermediate Arrester Characteristics

Ratings, kV rms	Range of application nominal system voltage, kV	Protective levels, per unit crest arrester rating			Durability characteristics				
		Front-of- wave sparkover	Switching surge sparkover	Discharge voltage, 10 kA, 8/20- μ s wave	Duty cycle initiating surge, crest amperes	Transmission line discharge, mi	High- current withstand, crest amperes	Pressure relief, rms symmetrical amperes	
Station class									
3-9	2.2-12.47	2.24-4.24	1.89-3.30	Test	1.57-1.77	10,000	150	65,000	65,000 25,000
12-15	13.2-18	2.12-2.83	1.89-2.42	not	1.57-1.70	10,000	150	65,000	65,000 25,000
21-48	18-46	2.09-2.56	1.80-2.29	required	1.56-1.70	10,000	150	65,000	40,000 25,000
60-120	69-138	1.99-2.24	1.60-1.94	1.60-1.80	1.56-1.69	10,000	150	65,000	40,000 25,000
144-240	161-287	1.83-2.22	1.57-1.70	1.57-1.61	1.56-1.79	10,000	175	65,000	40,000 25,000
258-312	345	2.06-2.17	1.56-1.70	1.57-1.61	1.56-1.58	10,000	200	65,000	40,000 25,000
372 or higher	500 or higher	1.94-2.10	1.65-1.70	1.44-1.58	1.54-1.60	10,000	200	65,000	40,000 25,000
Intermediate class									
3-6	2.4-7.2	2.47-2.83	2.24-2.83	Test not	1.77-2.36	5000	100	65,000	16,100
9-48	7.2-46	2.10-2.59	1.78-2.51	required	1.77-2.19	5000	100	65,000	16,100
60-120	69-138	1.76-2.26	1.63-1.84	2.06-2.43	1.77-2.02	5000	100	65,000	16,100

TABLE 27-8 Characteristics of a Commercial MOV-Type Device, HA Series, 480 V

Model number	Size, mm	Continuous rms voltage rating, V	Continuous dc voltage rating, V	Transient energy absorption, J	Peak current 8/20 μ s, A	Varistor voltage at 1-mA dc test current			Maximum clamping voltage at 200 A, 8/20 μ s, V	Typical capacitance, pF
						Min., V	Normal, V	Max., V		
V481HA32	32	480	640	450	25,000	670	750	825	1290	1300

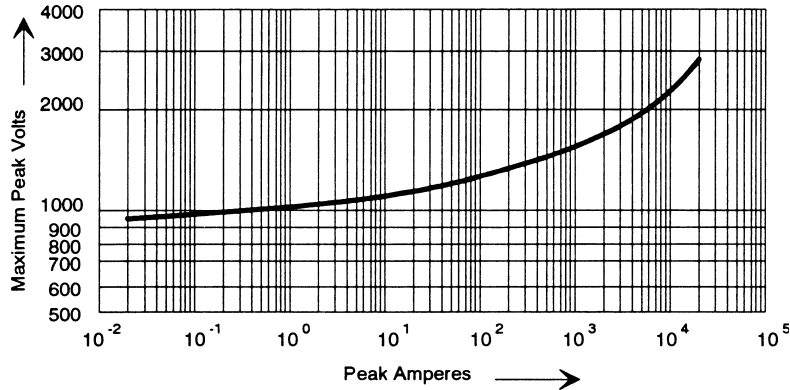


FIGURE 27-57 Voltage-current characteristic of transient voltage suppressor V481HA32, HA series.

The objectives of insulation coordination procedures also depend on the effects of insulation failure. In this respect, power apparatus may be grouped in two broad categories: (1) those that use air as insulation (external insulation) and (2) those that use solid or liquid dielectrics as insulating material (internal insulation). Insulation failure in devices of the first category is not as destructive as insulation failure in devices of the second category. With the exception of secondary effects, failure of air insulation is self-healing, since removal of the overvoltage will restore the insulation. For this reason, the objectives of insulation coordination for external insulation are typically the minimization of insulation failure. It is permissible to tolerate a small probability of insulation failure if this will minimize the cost. Probabilistic methods are pertinent for this purpose. On the other hand, the objective of insulation coordination for internal insulation is to disallow any insulation failure from any known causes. Adherence to this objective is dependent on the cost of the apparatus under protection. As an example, this objective is strictly observed for higher MVA-rating power transformers while for distribution transformers the cost of meeting the objective may not be justifiable. Because of this variability in objectives, the process of insulation coordination is examined separately for transmission lines, substations, overhead distribution systems, underground distribution systems, and industrial/commercial systems.

Transmission Lines. Overhead transmission lines use air or porcelain as the external insulating

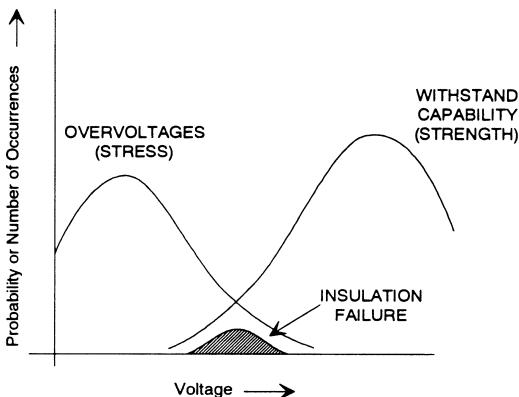


FIGURE 27-58 Statistical evaluation of insulation failures.

material. Flashovers across insulator strings or phase conductor to ground wire do not lead to catastrophic failures but rather to momentary outages. In other words, the insulation strength is quickly restored after arc extinction. For this system, the objectives of insulation coordination are to minimize the momentary outages at minimum cost. This is achieved through a procedure by which the cost of momentary outages is balanced against the cost of providing for overvoltage protection. The procedure is statistical, since many driving factors are statistical, for example, lightning strength and rise time. It is illustrated in Fig. 27-58, where the distribution of overvoltages is plotted as well as the distribution of withstand

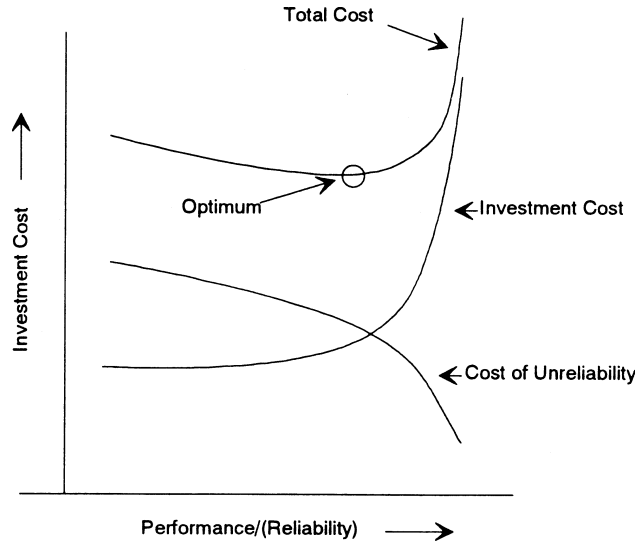


FIGURE 27-59 Optimal design procedures that provide best trade-off between performance (reliability) and cost.

capability. Outages may occur when the overvoltage exceeds the withstand capability. This procedure can be carried one step further, where the performance (reliability) of the system is balanced against cost of designs. This concept is illustrated in Fig. 27-59, where the optimum design is defined at the minimum of the total cost consisting of the investment cost plus the unreliability cost. A drawback of this method is the fact that, while the investment cost can be properly assessed, the cost of unreliability may be elusive and at best subjective. In any case, insulation coordination of overhead transmission lines involves the following basic tasks:

- Design of an effective shielding against direct lightning strokes
- Design of an adequate insulation strength to withstand power frequency, switching, and lightning overvoltages
- Design of an effective grounding system to minimize backflashovers

The design procedure typically consists of selecting a standard design and subsequently estimating the expected number of momentary outages. Design modifications are exercised if objectives are not met. In this section, we will be concerned with estimation of the number of momentary outages. This task involves the following procedure:

- Estimation of the number of lightning strokes in the area
- Estimation of the percentage of strokes reaching the line
- Estimation of number of shielding failures
- Estimation of probability of backflashover
- Effects of corona
- Summary of results

Estimation of the number of lightning strokes in the area. The ground flash density is defined as the number of lightning strokes (cloud to ground) per unit of area. It is preferable to use actual data on ground flash density if available. If not, then, as a first approximation, the ground flash density is taken to be approximately proportional to the thunderstorm activity, measured in thunderstorm days.

TABLE 27-9 Empirical Relationships between Lightning Ground-Flash Density and Annual Thunderstorm Days T

Location	Ground-flash density, number of ground flashes/km ² · year
India	$0.1T$
Rhodesia	$0.14T$
South Africa	$0.04T^{1.25}$
Sweden	$0.004T^2$ (approx.)
United Kingdom	aT^b ($a = 2.6 \pm 0.2 \times 10^{-3}$; $b = 1.9 \pm 0.1$)
United States (north)	$0.11T$
United States (south)	$0.17T$
United States	$0.1T$
United States	$0.15T$
U.S.S.R. (Former)	$0.036T^{1.3}$
World (temperate climate)	$0.19T$
World (temperate climate)	$0.15T$
World (temperate climate)	$0.13T$

Source: EPRI (1975).

Empirical formulas have been developed and are listed in Table 27-9. For the United States, the most commonly used formula is

$$N_1 = 0.12T \quad \text{or} \quad N_2 = 0.31T$$

where N_1 = ground flash density per square kilometer per year

N_2 = ground flash density per square mile per year

T = number of thunderstorm days

It must be emphasized that this formula should be viewed as an average and approximate only, since thunderstorm activity may vary from year to year and the lightning activity in a thunderstorm day may vary.

Estimation of the Percentage of Strokes Reaching the Line. The number of strokes reaching the line (shield wire or phase conductor) can be estimated with two basic models:

The geometric model

The electrogeometric model

These basic models have many variations, as many researchers have made improvements to improve their correlation to observed data.

The principle of the geometric model is illustrated in Fig. 27-60. The model postulates that the line casts a shadow around it of width W . Any ground flash which would terminate at the shadow of width W if the line was not present will be intercepted by the line. Assuming that the ground flashes are uniformly distributed over the surface of the ground, the following equation applies for the number of strokes to the line:

$$N_{l1} = 0.00012 WT$$

or

$$N_{l2} = 0.000193 WT \quad (27-2)$$

where N_{l1} = number of strokes to the line per kilometer of line length per year

N_{l2} = number of strokes to the line per mile of line length per year

W = width of the line shadow, m

T = number of thunderstorm days in the area

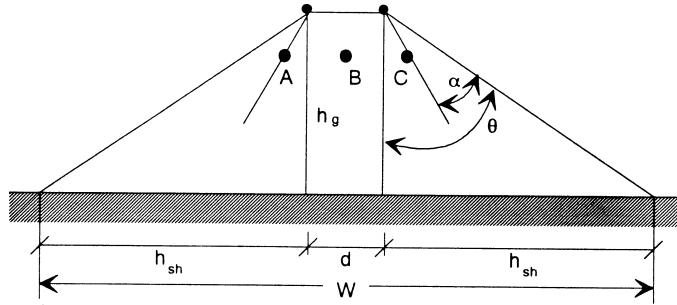


FIGURE 27-60 Illustration of application of the geometric model.

An expression for the shadow width is

$$W = 4h + d$$

where d = distance between shield wires (zero if only one shield wire)

h = effective height of the line, which can be approximated with $h = h_g + \frac{2}{3}(h_g - h_{gw})$

h_g = shield wire height at the tower or pole

h_{gw} = shield wire height at midspan

The geometric model is very simplistic. It fails to take into account that the striking distance of lightning is determined by the magnitude of the return stroke as well. An improved method is the so-called electrogeometric model. The principle of this model is illustrated in Fig. 27-61. This model is based on the observation that the point where the stepped leader of a lightning terminates is not determined until the stepped leader is within a striking distance. The striking distance is defined as the length of the final leg of the stepped leader which establishes contact with a ground object. The striking distance was

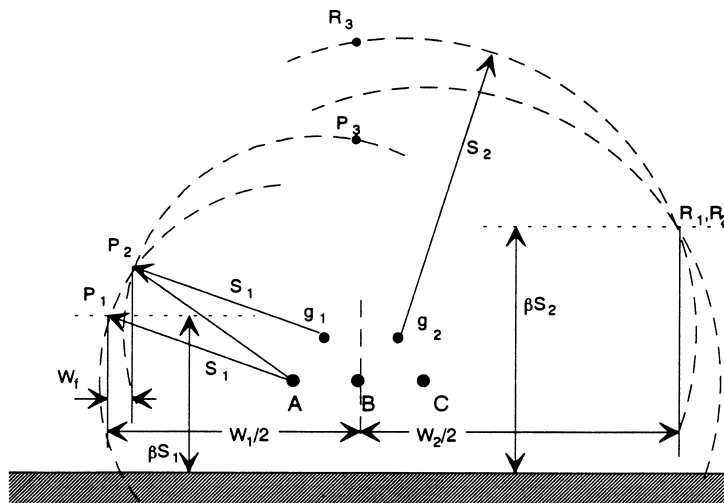


FIGURE 27-61 Illustration of application of the electrogeometric model. [Note: The value of β is a function of tower height. Anderson (1975) uses $\beta = 0.67$ for ultra-high-voltage (UHV) lines.]

TABLE 27-10 Proposed Equations for Determining the Striking Distance

 S = striking distance in meters; I_s = first return stroke current, kA

Proposed formula	Reference
$S = 2I_s + 30 (1 - e^{-0.147I_s})$	Darveniza (1979)
$S = 10 I_s^{0.65}$	Love (1973)
$S = 9.4 I_s^{0.67}$	Whitehead (1977)
$S = 8 I_s^{0.65}$	IEEE (1987)
$S = 3.3 I_s^{0.78}$	Suzuki (1981)
$S = 0.67 h^{0.6} I_s^{0.74}$	Erickson (1982)
$S = 1.57 h^{0.45} I_s^{0.69}$	Rizk (1994)

found to depend on the amplitude of the first return stroke. A number of empirical formulas have been proposed for determining the striking distance. Table 27-10 lists the most common ones.

The equation most commonly used in the United States is the second one listed in Table 27-10. Using a striking distance, which depends on stroke magnitude, generates a model, which suggests that the number of strokes intercepted by the line depends on their magnitude. Figure 27-61 illustrates the application of the method to compute the number of strokes terminating at the line for

two different stroke magnitudes, 7 and 12 kA. Specifically, for strokes of 7 kA, the striking distance is S_1 . For this striking distance, one can construct the width over which the strokes will be intercepted by the line. This width, W_1 , is shown in the figure. It is constructed by (1) drawing a line above ground at height βS_1 , where $\beta = 0.8$ (from Anderson 1968), (2) drawing a circle of radius S_1 with center at the phase conductor, and (3) drawing a circle of radius S_1 with center at the shield wire. The construction of the width W_2 for strokes of 12 kA is also shown in the figure. The computed widths W_1 and W_2 can be used in Eq. (27-2) to estimate the number of strokes to the line. It should be understood that the process is repeated for several stroke magnitudes, spanning the distribution of lightning current magnitudes; then all the results are utilized to compute the statistical distribution of the expected strokes to the line. The average value can be extracted from this distribution.

Estimation of Number of Shielding Failures. It is important to know how many of the strokes reaching the line will actually terminate on a phase conductor or on a shield wire. The consequences are obvious. A lightning stroke terminating at the phase conductor and of sufficient magnitude will most likely result in a flashover. This is obvious when one considers the magnitude of the overvoltage. When shielding failure occurs and the lightning stroke terminates on the phase conductor, it generates an overvoltage on the stricken phase which is given by

$$v_s(t) = \frac{1}{6} (Z_g + 2Z_t)i(t)$$

and an overvoltage on the other two phases which is given by

$$v_n(t) = \frac{1}{6} (Z_g - Z_t)i(t)$$

where $i(t)$ = lightning stroke current

Z_g = characteristic impedance for the ground mode of propagation of surges along the line

Z_t = characteristic impedance for the line mode of propagation of surges along the line

$v_s(t)$ = lightning overvoltage on the stricken phase

$v_n(t)$ = lightning overvoltage on any one of the other two phases

For a typical transmission line design

$$Z_g \approx 800 \Omega$$

$$Z_t = 400 \Omega$$

In this case, the overvoltage is

$$v_s(t) \approx 300i(t)$$

$$v_n(t) \approx 60i(t)$$

Obviously, a shielding failure for a lightning stroke of 20 kA will generate an overvoltage of about 6 MV, which most likely will cause a flashover. On the other hand, a lightning stroke

terminating on a shield wire will result in much lower overvoltages, if the transmission line is effectively grounded. It is, of course, possible that the overvoltages resulting from a lightning stroke to the shield wire will be of such magnitude as to cause a flashover from the shield wire or tower to the phase conductor. This event is known as a *backflashover*. In any case, the line shielding must be designed in such a way that the number of times lightning reaches a phase conductor is minimized. Occurrences of such incidents are termed *shielding failure*.

The electrogeometric model provides an adequate tool to determine shielding failure. The basic premise of the method is defined in Fig. 27-61. Consider the striking distance S_1 for a lightning stroke of magnitude I_1 . Consider also the line above ground at a height βS_1 , the circle of radius S_1 with center at phase A, and the circle of radius S_1 with center at shield wire g_1 . The intersections of these circles define the points P_1 and P_2 . The electrogeometric model states that any stepped leaders, which reach the arc P_1P_2 and of magnitude less than I_1 will terminate on the phase conductor A, resulting in a shielding failure. Any stepped leader reaching the arc P_2P_3 will be attracted by the shield wire. The percentage of lighting strokes of magnitude I_1 or lower, which will reach a phase conductor, can be estimated by comparing the length of the arc P_1P_2 to the length of the arc P_2P_3 . This process can be repeated for various stroke magnitudes. Subsequently, and utilizing the statistics of the stroke magnitude distribution, the probability distribution of shielding failures can be computed. The expected number of shielding failures can also be computed.

For lightning strokes of a certain magnitude, the striking distance will be such that the points P_1 and P_2 may collapse to one point. This condition is illustrated in Fig. 27-61 for a different magnitude of stroke current I_2 , where the points R_1 and R_2 coincide. Any stepped leader resulting in stroke current magnitude I_2 or higher and reaching the arc R_2R_3 will terminate on the shield wire. Any other stepped leaders reaching points to the right of points R_2 will terminate to the ground. In this case, the line is shielded for lighting strokes of magnitude greater than I_2 . Now assume that the line insulation can withstand the overvoltages resulting from a direct hit on a phase conductor of magnitude I_2 . In this case, a shielding failure for lighting strokes of magnitudes I_2 or lower will not result in a flashover. The line is said to be *effectively shielded*.

An extension of this statement results to the concept of the critical striking distance. The critical striking distance is the striking distance for the smallest lightning stroke current magnitude, which, if it terminates on a phase conductor, will cause a flashover. The critical striking distance can be used to define the location of shield wires which will provide an effective shielding.

Estimation of Probability of Backflashover. Backflashover can occur when the transmission tower voltage at the location where the phase insulators are suspended (crossarms) becomes so high as to initiate an arc between the crossarm and the phase conductors. The driving force for initiating the arc is the voltage across the insulator which depends on many factors

Voltage at the crossarm due to the lightning stroke

Induced voltage on the phase conductor due to surges on the shield wire generated by the lightning stroke

Power frequency voltage at the phase conductor

Tower footing impedance

Traveling-wave phenomena along the tower

Lightning strokes to the tower result in the highest overvoltage at the top of the tower as compared to overvoltages from lightning strokes on the shield wire along the span. As an example, consider a lightning stroke of crest 10 kA and rise time $1 \mu\text{s}$ terminating on the shield wire of a transmission line. For simplicity, neglect the phase conductors. The system is illustrated in Fig. 27-62a. All tower ground resistances are 80Ω . The parameters of the shield wire, for the example under consideration, are

$$L = 2.7 \mu\text{H/m}$$

and

$$C = 6.58 \times 10^{-12} \text{ F/m}$$

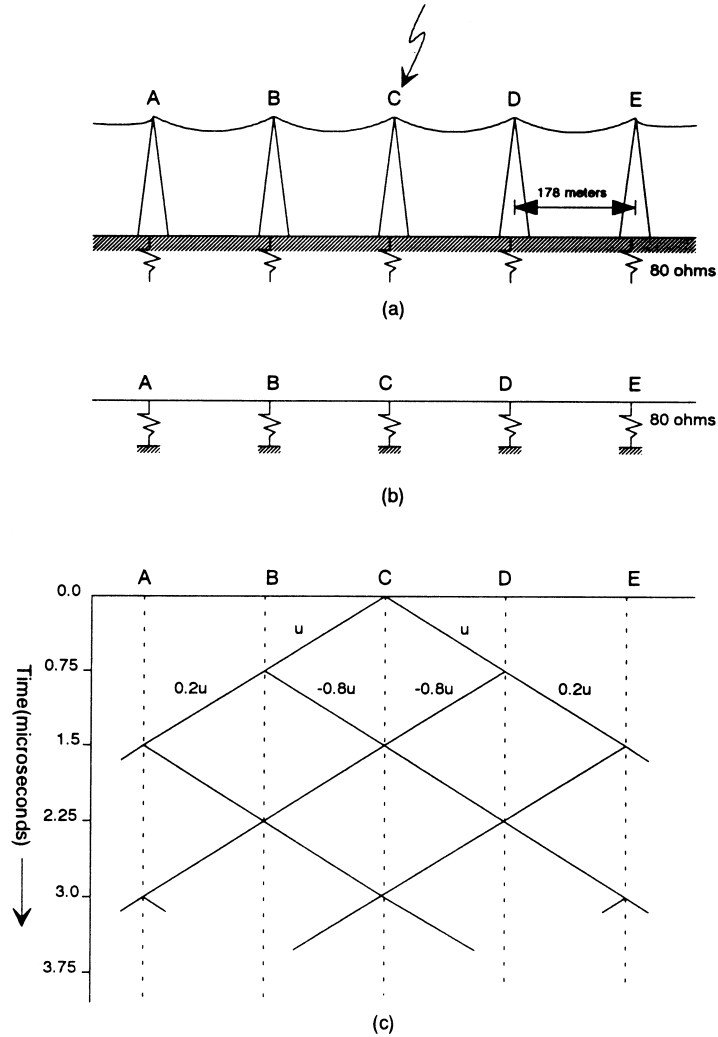


FIGURE 27-62 Simplified calculations of overvoltages resulting for a lightning stroke to a tower: (a) schematic; (b) simplified circuit; (c) Bewley diagram.

The characteristic impedance of the shield wire is $Z = \sqrt{L/C} = 640 \Omega$, and the speed of propagation of surges is $v = 1/\sqrt{LC} = 237 \text{ m}/\mu\text{s}$. The travel time from one tower to the next is $0.75 \mu\text{s}$. To further simplify the computations, traveling-wave phenomena along the tower are neglected, resulting in the simplified circuit of Fig. 27-62b. The reflection and transmission coefficients at the tower are $\alpha = -0.80$ and $\delta = 0.20$. The Bewley diagram for this circuit is illustrated in Fig. 27-62c, where $u(t)$ is computed as

$$u(t) = R_{\text{eq}} i(t) = 64i(t)$$

Thus, $u(t)$ will have a rise time of $1 \mu\text{s}$ and crest of 640 kV. By summing up all the waves arriving at point C, the voltage waveform c1 of Fig. 27-63 is obtained. This procedure can be repeated,

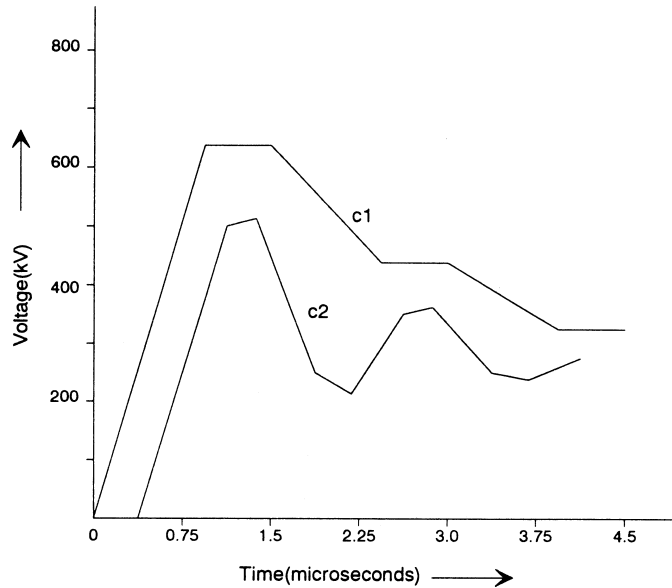


FIGURE 27-63 Lightning overvoltages at top of tower; in c1 the lightning stroke terminates at tower top, and in c2 the lightning stroke terminates at midspan.

assuming that the same lightning stroke terminates at the shield wire in the middle of the span. The resulting overvoltage at the top of the tower C is shown as waveform c2 in Fig. 27-63. Note that the crest of this waveform is much lower. In reality, the tower footing impedance is frequency-dependent and traveling-wave phenomena along the tower affect the overvoltages. Figure 27-64 illustrates a typical voltage waveform across the phase insulators using a rather sophisticated model (Cokkinides and Meliopoulos 1988). Note that reflections from adjacent towers quickly reduce the voltage across the phase insulators. Also, the crossarm voltage is in general lower than the top of the tower voltage. As a result, bottom phase insulators, in general, experience the highest

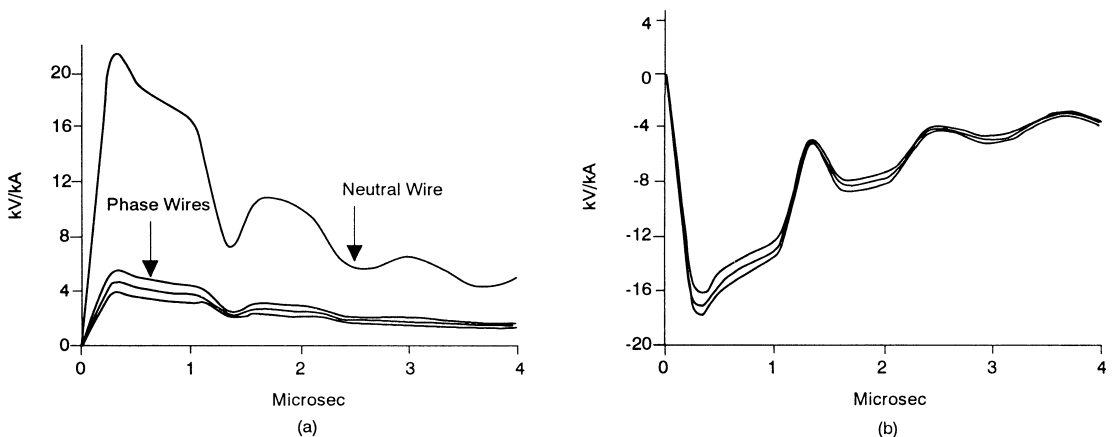


FIGURE 27-64 Typical voltage waveforms across phase insulators due to lightning: (a) transient voltage of phase conductors and shield wire; (b) transient voltage across insulators.

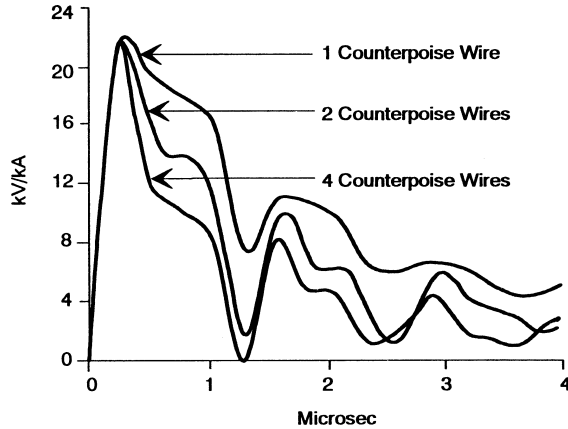


FIGURE 27-65 Illustration of effects of tower grounding on voltage at top of tower due to a lightning stroke at the tower.

overvoltage for backflashover. The tower ground also affects the overvoltage. As an example, Fig. 27-65 illustrates the effect of tower grounding on the lightning voltage at the top of the tower. Note that the voltage at the top of the tower is not affected by tower grounding for the first approximately $0.2 \mu\text{s}$ after lightning initiation. However, the overall overvoltage waveform is drastically affected by tower grounding. Since the characteristics of arc initiation across the insulator string have a volt-time characteristic, it is very important to examine the effect of voltage waveform on backflashover initiation.

CIRGE has accepted the following volt-time curve for line insulator flashover, which is consistent with the work of Darveniza et al. (1975, 1979) and Whitehead (1977)

$$V_f = 0.4W + \frac{0.71W}{t^{0.75}}$$

where W = line insulator length in meters

t = time to breakdown in microseconds

V_f = flashover voltage in megavolts for negative surges

One should compare the volt-time characteristic to the actual voltage across the phase insulators to determine whether a backflashover will occur. Figure 27-66 illustrates such a construction where the insulator withstand capability versus time of a 1-m-long insulator string is superimposed on the actual voltage experienced by the insulator.

Effects of Corona. The overvoltage occurring at a phase conductor or shield wire establishes an extremely high-voltage gradient perpendicular to the conductor. This gradient, wherever it exceeds the withstand capability of air, will generate electric discharges, which will electrify the air surrounding the conductor. This phenomenon is known as *corona*. Corona increases the apparent radius of the conductor while it does not affect the geometric mean radius of the conductor. As a result, it decreases the characteristic impedance of the line and the level of overvoltages resulting from lightning.

The voltage gradient (electric-field intensity) around an energized conductor is approximately

$$E = \frac{V}{r \ln(2h/a)}$$

where V is the conductor voltage, r is the distance from the conductor centerline, h is the conductor height above the earth, and a is the conductor radius.

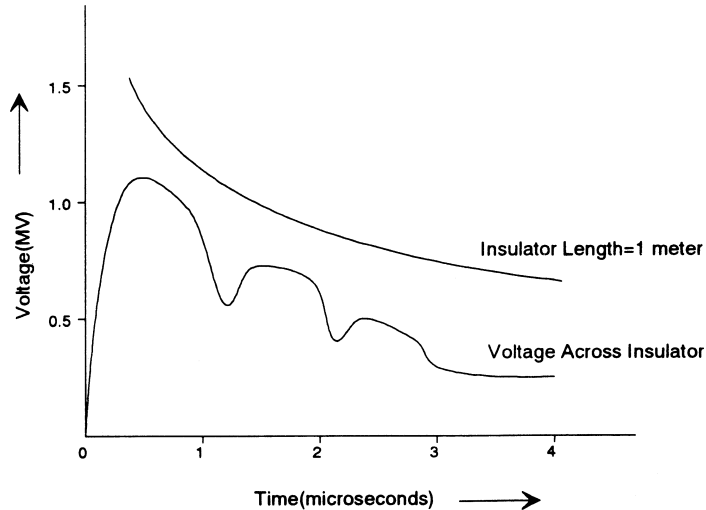


FIGURE 27-66 Insulator voltage-time curve and insulator voltage.

The value of 15 kV/cm is accepted as the electric-field intensity required to establish corona. Thus, corona will exist in a radius a_c such that

$$15 \text{ kV/cm} = \frac{V}{a_c \ln(2h/ac)}$$

As an example, a conductor 50 ft above the earth which experiences an overvoltage of 3.5 MV will establish corona at a radius $a_c = 2$ ft.

Summary of results. In summary, methods have been discussed for design of line-shielding systems, estimation of shielding failure, estimation of overvoltage stresses across insulators, and methods to determine the possibility of flashover across an insulator. There is a considerable uncertainty with almost all parameters and models affecting shielding failure, magnitude, and waveform of overvoltage across insulators, etc. This uncertainty can be dealt with by using probabilistic methods. Monte Carlo simulation is utilized for this purpose and is described in Sec. 27.8.

Substation Lightning Insulation Coordination. Substations typically comprise equipment such as transformers, bus work, breakers, reactors, and capacitor banks etc. This equipment must be protected against lightning overvoltages. As a rule, substations are shielded against direct lightning strikes on phase conductors. Thus, lightning overvoltages in a substation may occur for the following reasons:

1. Backflash due to a strike in the shield of the substation
2. Direct lightning hit due to shield failure
3. Lightning surges from lines (most common)
 - a. Line shielding failure
 - b. Line backflashover
 - c. Induced voltage

The overvoltage protection of substations consists of shielding against direct lightning strikes and application of protective devices (surge arresters) to protect specific power apparatus.

Substation shielding methods are similar to those applied for transmission lines. One can use the geometric model or the electrogeometric model to determine the effectiveness of the shielding wires,

masts, etc. The application of the electrogeometric model for substation shielding analysis is more complex since the analysis must be performed on a three-dimensional basis as opposed to a two-dimensional basis for a transmission line. A simplified variation of the electrogeometric model for the three-dimensional problems is the so-called rolling-sphere method. The basic idea of the rolling-sphere method is illustrated in Fig. 27-67a. Let S_c be the critical striking distance as defined for transmission lines:

$$S_c = 10I_c^{0.65}$$

where I_c is the critical stroke current, kA, as defined for transmission lines. The rolling-sphere method postulates that by rolling a sphere of radius S_c over the shield system of the substation, the protected equipment are those which are not crossing the path of the sphere as is illustrated in Fig. 27-67. This method provides a simple procedure to design an effective shielding system for the substation. Figure 27-67b provides a visualization of the application of this method to an actual substation.

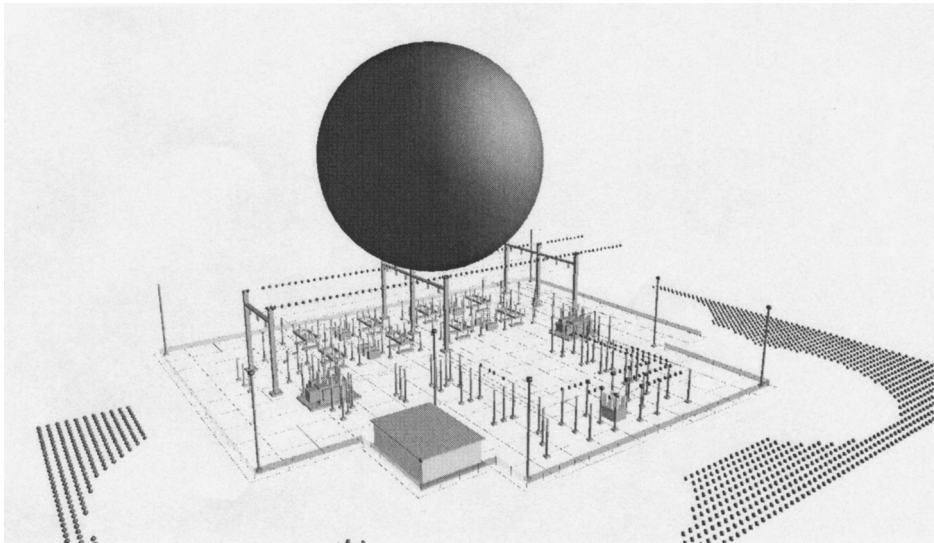
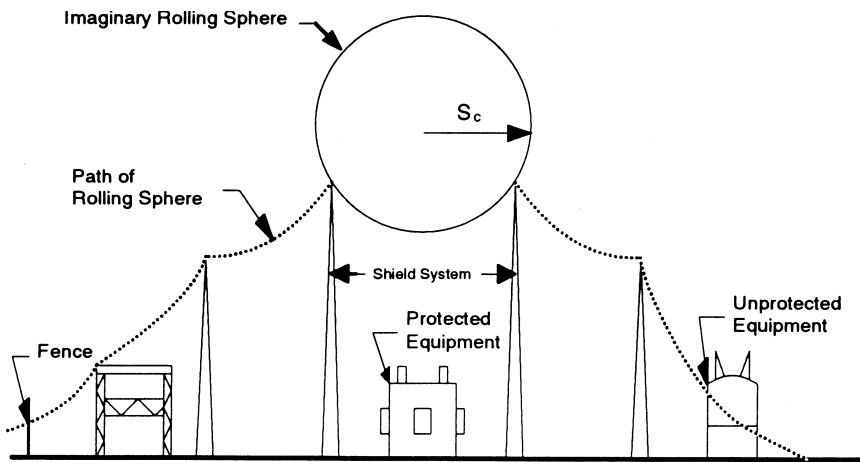


FIGURE 27-67 Illustration of the basic idea of the rolling-sphere method.

In addition to the shielding system, protection must be provided against overvoltages resulting from (1) lightning strikes to the shielding system and (2) surges entering the substation from the transmission lines (which are the most common). The magnitudes of the overvoltages in (1) above depend on the design of the grounding system. On the other hand, the overvoltages from (2) above depend on many factors, such as distance of point of initiation and source of surge (direct hit, induced). These overvoltages are typically limited by the insulation level of the transmission line. Since the usual case is that the substation equipment will have a BIL below the insulation level of the lines connected to the substation, overvoltage protection for the substation equipment must be provided.

The application of protective devices (surge arresters) for the protection of power transformers is illustrated in Fig. 27-68. The application procedure consists of the following steps:

1. Select arrester rating (preliminary).
2. Determine arrester protection levels
 - $V_{p, \text{fow}}$ = arrester protection level for a front of wave
 - $V_{p, d}$ = arrester protection level for a full-impulse wave
 - $V_{p, ss}$ = arrester protection level for a switching impulse
3. Determine transformer withstand capability
 - V_{foww} = front-of-wave withstand
 - V_{cww} = chopped-wave withstand
 - BIL = basic insulation level
 - BSL = basic switching insulation level
4. Plot arrester protection levels and transformer withstand capability on a common coordinate system, as illustrated in Fig. 27-68.
5. Determine protection margins.
6. If protection margins are not higher than the minimum recommended, select the next-lower arrester rating that is compatible with the normal operating voltage of the system, and go to step 2. Otherwise, go to step 7.
7. Determine whether arrester has adequate energy absorption capability for the application.

This procedure is pertinent for application of surge arresters near the transformer. If there is a separation distance between arrester and transformer, the effects of separation must be accounted for. Specifically, separation results in deterioration of protective margins, as illustrated in Fig. 27-69. The figure shows an application of an ideal arrester 15 m away from the transformer. The ideal arrester

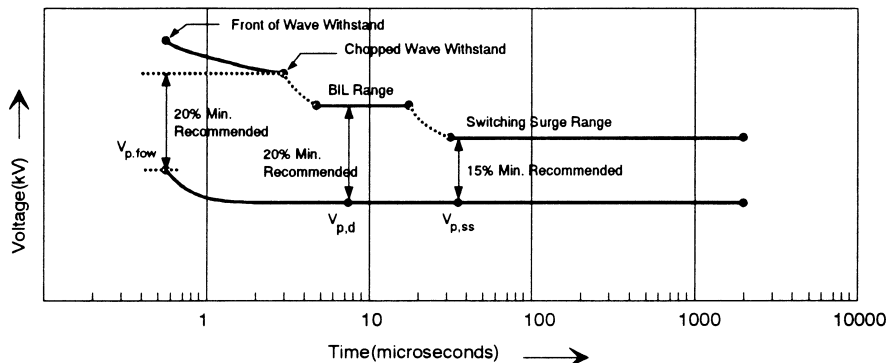
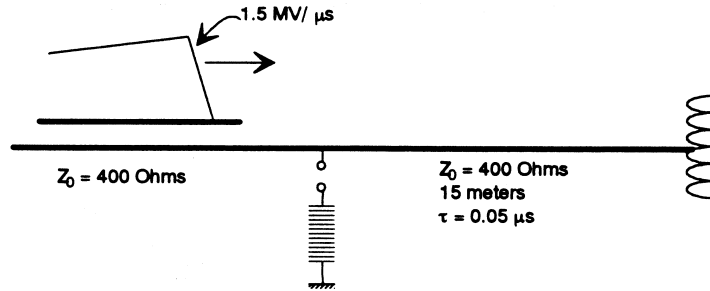
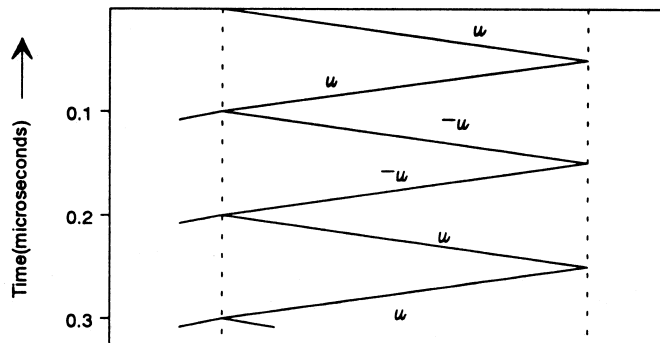


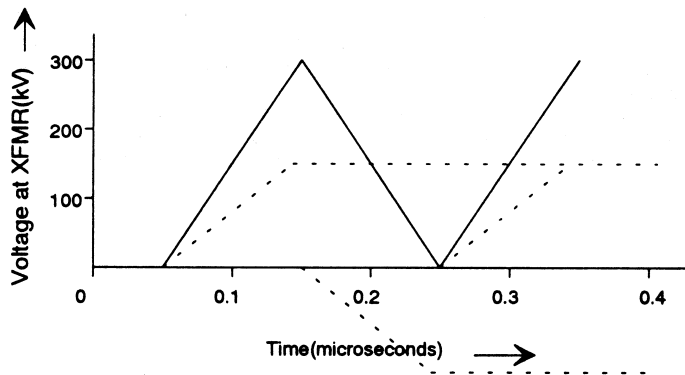
FIGURE 27-68 Application of surge arresters for protection of power transformers.



(a)



(b)



(c)

FIGURE 27-69 Example of arrester-transformer separation effects: (a) system configuration; (b) Bewley diagram; (c) voltage at transformer.

is rated 150 kV. Because of the separation distance, the overvoltage reaching the transformer will be 300 kV, double the protective level of the arrester.

Distribution System Overvoltage Protection. Distribution circuits are typically not insulated to withstand direct lightning strokes. As a result, direct strikes will cause a flashover. Direct strikes on distribution lines are not frequent since the poles are not as high and therefore are shielded from trees and structures. On the other hand, distribution lines may be vulnerable to overvoltages resulting from lightning strokes to nearby trees, ground, or other objects. These voltage surges are known as *induced lightning voltages* and are injected into the power system through coupling. The coupling can be conductive through the conductive soil and the power system grounding structures, inductive, or capacitive. In a typical situation, all the coupling mechanisms may be present resulting in a voltage surge to the power system. These voltages are called *induced voltage surges* and are generally much lower than those occurring after a direct strike. Specifically, they rarely exceed 500 kV. The induced lightning overvoltages are of concern for distribution lines 35 kV or below. Higher kilovolt-level lines (i.e., 69 kV and above) have sufficient insulation to withstand induced voltage surges.

The mechanism of induced voltage surges is illustrated in Fig. 27-70. A lightning stroke terminating at a location near a distribution line induces a surge on the line through conductive, inductive, and capacitive coupling. Several models to estimate the level of the induced voltage surges have been reported in the literature (Eriksson et al. 1982; Liew and Mar 1986). A simplified formula suggests the following induced voltage

$$v_p = Z_0 I h \cdot \left[\left(\frac{1}{2y} \right) \frac{1 + (x + \beta y)}{\sqrt{x^2 + 2y^2 + 2\beta xy - \beta^2 y^2}} + \frac{2\beta x + y}{y^2 + (2\beta x + y)^2} \cdot \frac{1 + 2\beta^2 x + \beta y - \beta x}{\sqrt{x^2 + 2y^2 + 2\beta xy - \beta^2 y^2}} \right]$$

where $\beta = 0.004I^{0.64} + 0.068$ first stroke
 $= 0.004I^{0.86} + 0.18$ subsequent strokes
 Z_0 = distribution line characteristic impedance
 I = stroke current crest

The terms x , y , and h are as illustrated in Fig. 27-70. In addition, many measurements of induced voltage surges have been performed which practically verify the available models.

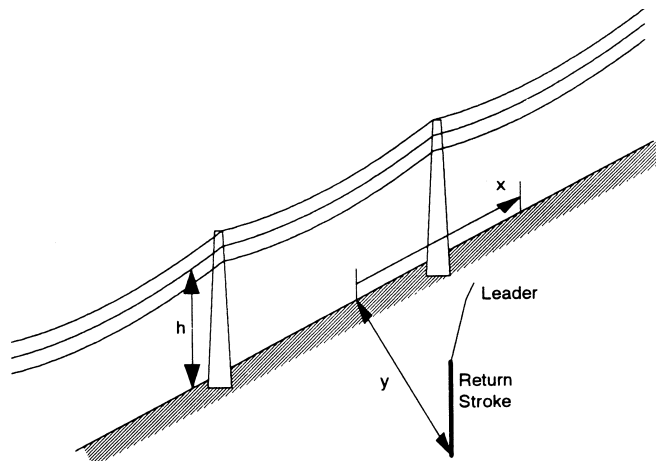


FIGURE 27-70 Illustration of lightning stroke near a distribution line.

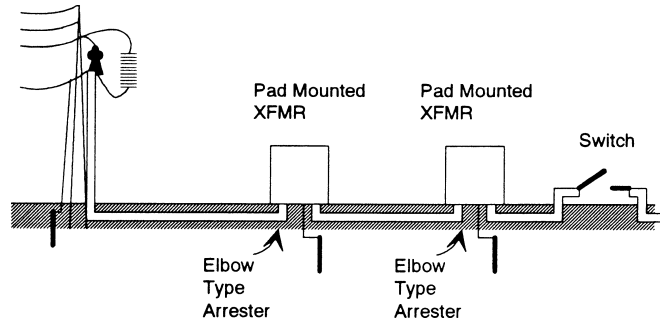


FIGURE 27-71 Typical overvoltage protection scheme for underground residential distribution (URD) systems.

Induced voltage surges on distribution lines are quite frequent. It is therefore necessary to insulate distribution lines to withstand these surges. This translates into the requirement of a 300 BIL for distribution lines. In addition, power apparatus, connected to distribution lines and with BIL lower than the induced voltage surges, such as distribution transformers (typically the BIL of distribution transformers is 100 kV) must be protected. It is practical to protect transformers with surge arresters of appropriate ratings.

Underground Distribution System Overvoltage Protection. A typical configuration of an underground distribution system is shown in Fig. 27-71. Typically a surge arrester will be applied at the riser pole. Underground residential distribution systems present a relatively low characteristic impedance (30 to 50 Ω). When a transient (surge) reaches the URD system through the high-surge-impedance overhead system, and because of the presence of a surge arrester at the riser pole, the surge transmitted to the cable will be of very fast rise time, typically a small fraction of a microsecond.

TABLE 27-11 Typical Basic Insulation Levels for Cables

Cable kV class	Typical BIL	Recommended arrester rating
15	95	9
25	125	18
34.5	150	25

The magnitude of the surge is determined by the characteristics of the arrester. This surge will propagate along the cable and will double when it arrives at an open point or at the end of the cable where a transformer may be present. If this overvoltage is below the BIL level of the URD cable, no additional protection is required. However, the BIL of typical URD cable is relatively low. As an example, Table 27-11 illustrates the typical BIL for the most usual cable classes. In most cases, if a cable is

protected with a surge arrester at the riser pole only (of the recommended arrester rating), it is possible that the overvoltage at the open end of the cable exceeds the BIL of the cable with the potential of failure. Use of surge arresters at the open ends, or, better yet, use of elbow type arresters at each transformer, drastically improves cable and transformer protection.

Overvoltage Protection of Industrial and Commercial Systems. Industrial and commercial power systems are subject to overvoltages resulting from lightning or switching operations. By far, lightning overvoltages are the most stressful. Since these systems are interconnected to power systems, disturbances on the power system will be transmitted to them. These systems are also subjected to direct lightning. Therefore, these systems also require shielding against lightning. Typically, a grounding system will be installed as well as a lightning protection system (shielding) to divert any direct lightning

strokes to ground. This grounding system is referred to as *external grounding* to distinguish it from the so-called internal grounding, which refers to the grounding system of various equipment in the facility. The external grounding systems of industrial/commercial power systems are interconnected to the power system, as shown in Fig. 27-72. The lightning protection system is basically a shielding system designed to route the lightning surges into the external grounding system for the purpose of minimizing potential differences within the facility. A system like this is subjected to lightning overvoltages which may enter from a number of points. Table 27-12 lists a number of possible points of entry. A coordinated design of the external grounding system, lightning protection system, and internal grounding system can provide a system, which is hardened against lightning and other sources of overvoltages. The effectiveness of the system can be assessed with analysis by using the methods discussed in this section.

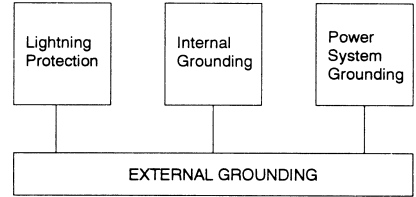


FIGURE 27-72 Conceptual description of the grounding system of an industrial or commercial facility.

TABLE 27-12 Lightning Points of Entry

Air terminals
Communication towers (if present)
Power system grounding
Fence

27.8 MONTE CARLO SIMULATION-BASED METHODS

In many parts of the globe, the performance of electrical installations is affected by lightning. In this case, it is important to design the system in such a way that outages from lightning are minimized. Typically, transmission lines, substations, and commercial and industrial buildings are the focus of the design process. Because lightning parameters present substantial variability, the effects of lightning must be evaluated on a statistical basis. Other parameters that affect system performance may also present substantial variability. One important parameter is soil resistivity, which affects ground impedances and therefore lightning overvoltages. Monte Carlo simulation methods are well suited to evaluate the effects of these parameters on system performance. A simplified description of a Monte Carlo simulation, given by Moussa and Wehling (1992), considers two parameters with substantial variability, and is illustrated in the following sequence of steps:

1. Generate a sample of lightning stroke described with respect to (a) crest magnitude and (b) rise time.
2. Generate a sample of soil resistivity.
3. Generate a sample of power frequency voltages.
4. Compute probability of shielding failure.
5. Perform an experiment and determine the lightning termination point (phase conductor, shield wire, etc.).
6. Compute transient voltages in system for conditions described above.
7. Perform effects (failure) analysis (compare voltage stresses on insulation against withstand capability).
8. If number of trials exceeded allowable, go to step 9. Otherwise go to step 1.
9. Generate histograms of maximum overvoltage and backflashover.

It should be understood that this Monte Carlo simulation requires that a good analysis procedure should be available to reliably compute the overvoltages on the insulation. Such models have been developed and are available. Detailed description of these methods is beyond the scope of this text. Instead, some typical results will be presented and discussed.

A typical application of these methods is to evaluate the performance of a specific power line. Figures 27-73 and 27-74 respectively illustrate examples of shielding analysis for two different

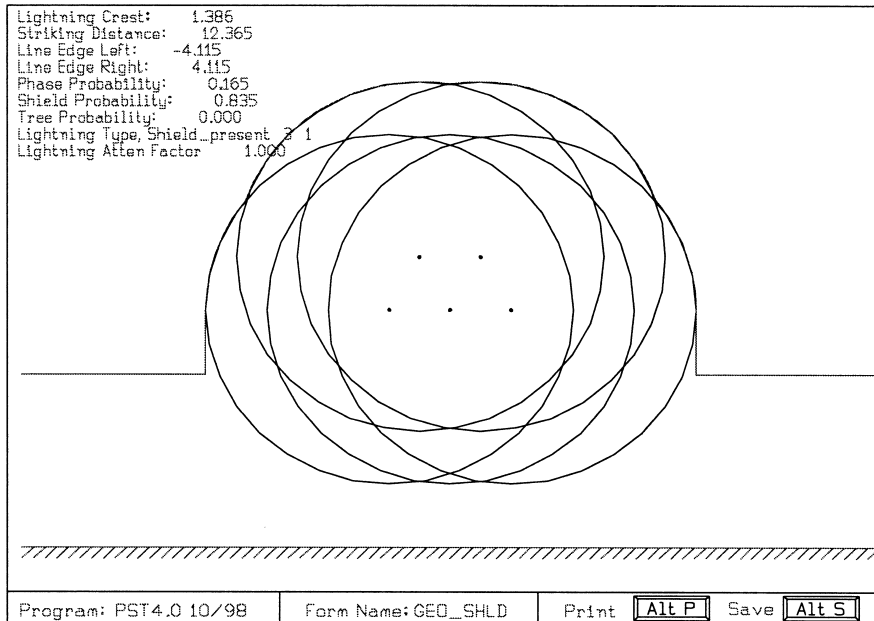


FIGURE 27-73 Example of shielding analysis. Lightning crest is 1.386 kA. There is a finite probability of direct strike on the phase conductor.

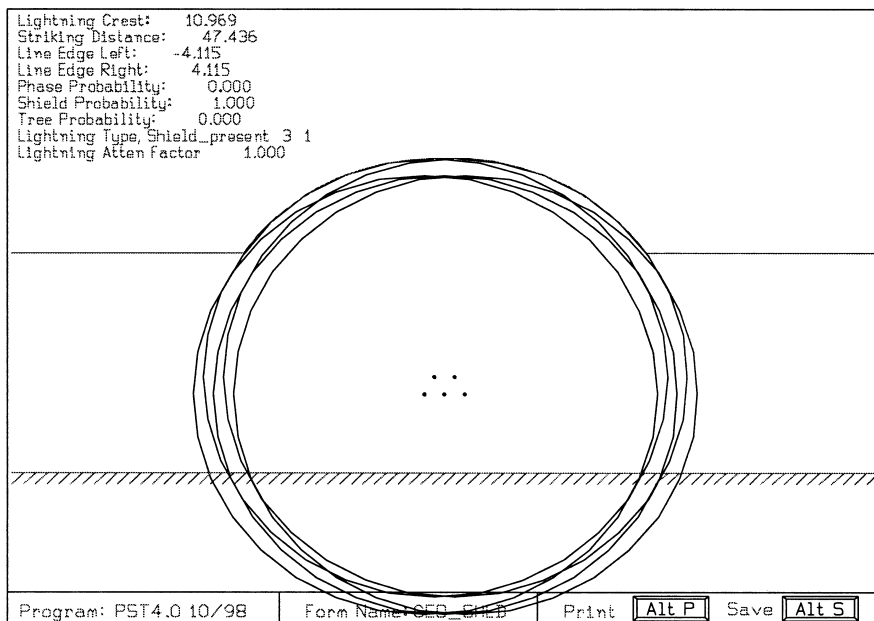


FIGURE 27-74 Example of shielding analysis. Lightning crest is 10.969 kA. The probability of direct strike on the phase conductor is zero.

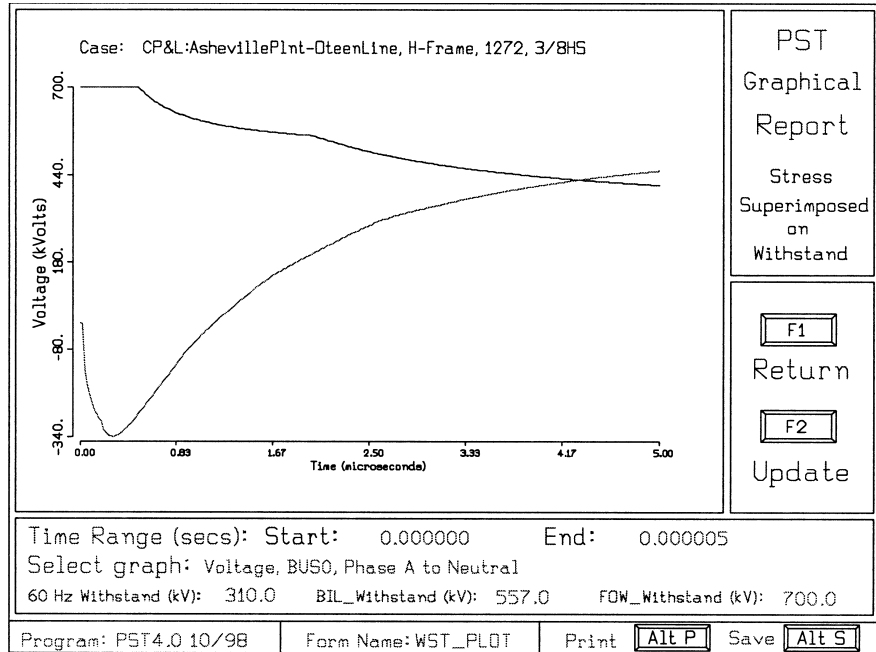


FIGURE 27-75 Example of effects analysis. Overvoltage across insulator exceeds the volt-time withstand curve of the insulator.

samples (trials) of the Monte Carlo simulation. Note that for the same system, when the current is low, there is a probability of shielding failure. As the lightning current increases, shielding failure may be eliminated.

Figures 27-75 and 27-76 respectively illustrate examples of effects (failure) analysis for two different trials of the same system. Note that the conditions illustrated in Fig. 27-75 will lead to insulation flashover, while the system will withstand the conditions illustrated in Fig. 27-76.

The results of the Monte Carlo simulation are illustrated in Fig. 27-77. Note that for this case, which refers to a transmission line, there is a small probability of direct hit to the phase conductor and that the average crest of direct hit is 8.17 kA s. The results are in terms of expected number of flashovers per 100 mi of the line and per year.

27.9 LIGHTNING ELIMINATION DEVICES

It is always desirable to eliminate the destructive effects of lightning on electrical equipment. Benjamin Franklin was the first to invent the lightning rod that provides a sacrificial path for the flow of the lightning current. Professor Moore (1997) has researched Franklin's investigations and points out that, initially, Franklin believed that his lightning rod would eliminate lightning. Experimental observations have shattered this belief and Franklin accepted the fact that the lightning rod does not eliminate lightning but rather behaves as the sacrificial electrode for the termination of lightning so that other structures in the vicinity can be protected. This observation developed into the modern shielding theory we use for design purposes and which was discussed earlier.

The desire to seek a device that prevents lightning did not die. The Czech scientist Prokop Divisch has advocated this goal in 1754. The basic idea in lightning prevention is to provide multiple points of

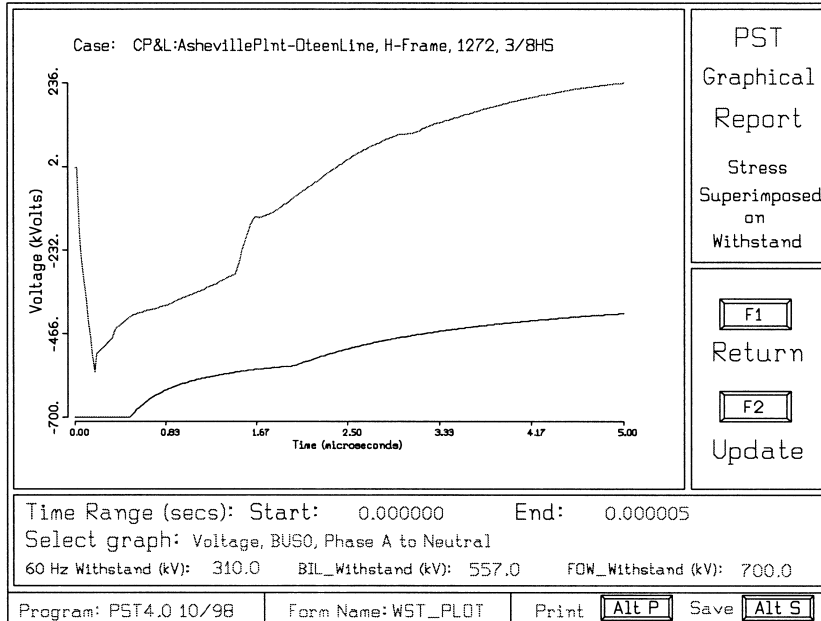


FIGURE 27-76 Example of effects analysis. Overvoltage across insulator does not exceed the voltage-time withstand curve of the insulator.

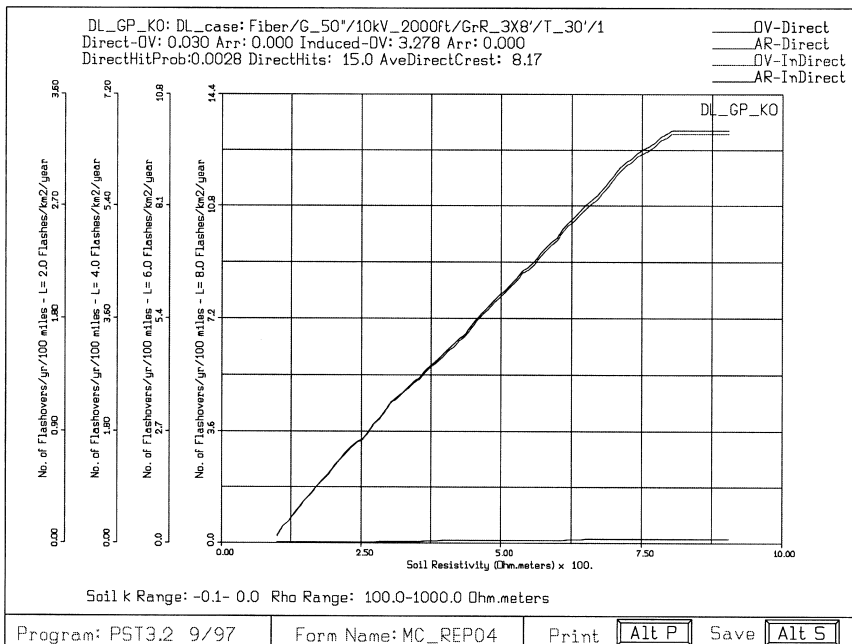


FIGURE 27-77 Example of Monte Carlo simulation results.

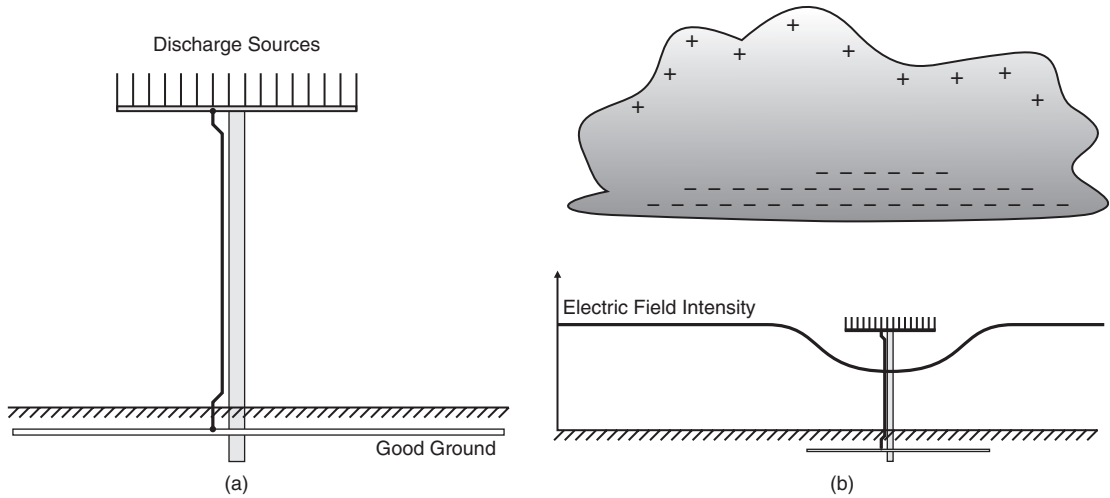


FIGURE 27-78 Conceptual illustration of a lightning elimination system showing (a) a good ground with discharge sources and (b) the discharge into the electrified cloud.

discharge to neutralize an electrified thundercloud. In theory, these charges can reach the electrified cloud and prevent the initiation of lightning. In fact, in 1930 a patent was awarded to J. M. Cage of Los Angeles for a lightning prevention device consisting of *point-bearing* wires suspended from a steel tower for the purpose of protecting petroleum storage tanks. Later, in 1971, lightning prevention systems were commercialized.

There are many technologies of lightning prevention systems: (a) active air terminal that generate ions which blend into the atmosphere to minimize the electric field around the protected facility, (b) terminals with multiple sharp edges that ionize the air around the terminal for the purpose of minimizing the electric field around the protected facility and (c) umbrella terminals, which provide a smooth surface that minimizes the maximum electric field around the protected facility. As an example the theory of operation of technology (b) is discussed. Specifically, the basic idea of this technology is illustrated in Fig. 27-78. The system consists of sharp objects (discharge sources), which are electrically connected to a good grounding system (Fig. 27-78a). The theory is that the discharge released by the discharge sources into the atmosphere will reach the electrified cloud (Fig. 27-78b) and will partially neutralize it.

The success of lightning prevention systems has not been as advertised. There is indisputable field evidence that the *lightning elimination devices* cannot eliminate lightning. On the other hand, there are cases in which these devices helped reduce the frequency and extent of damage from lightning (Moussa 1998). The present knowledge and theories of lightning are consistent with this field experience.

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